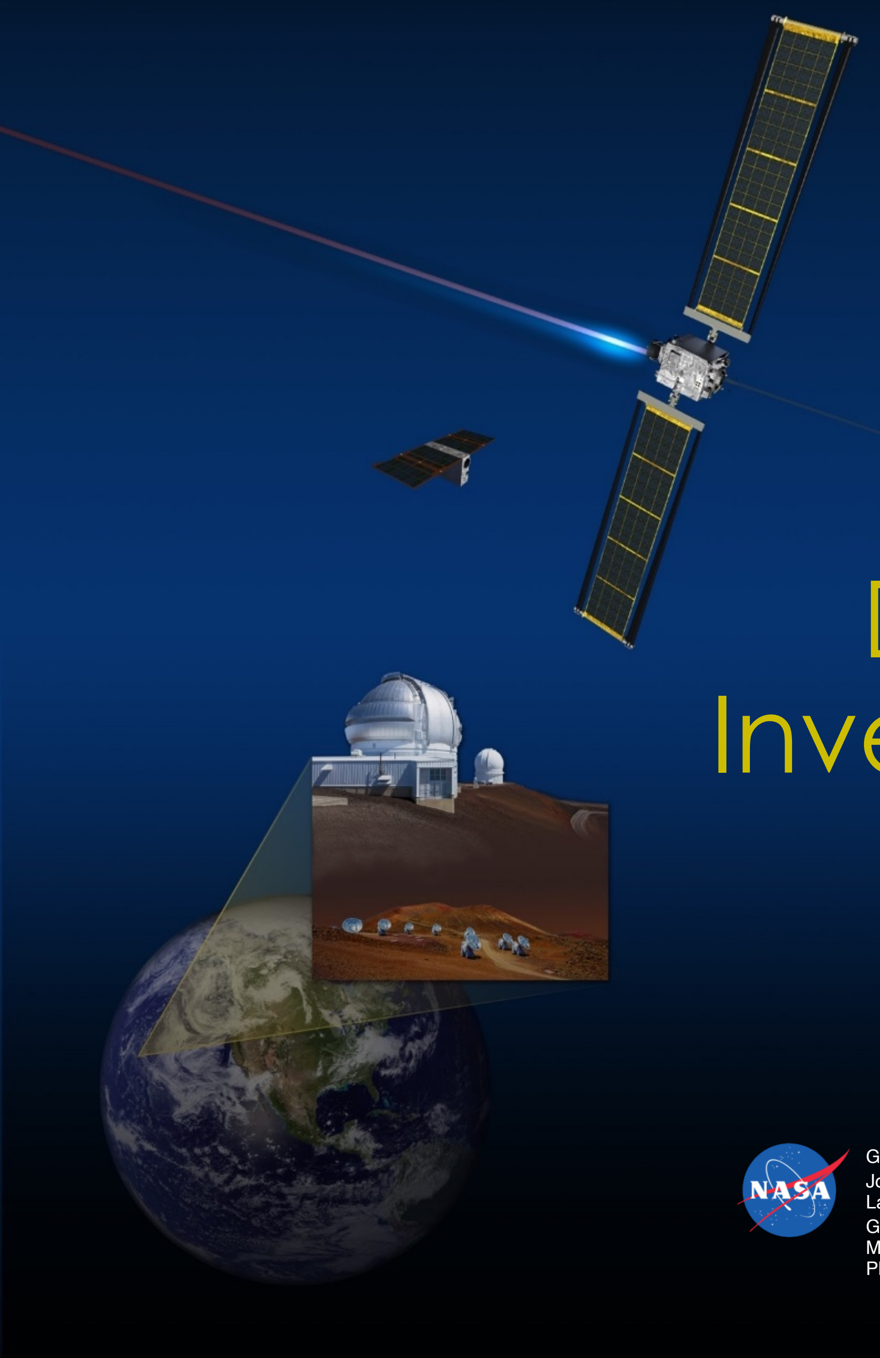


DART
Double Asteroid Redirection Test

Didymos Binary System Dynamics & Physical Properties Investigations for the DART Mission

Including Outcomes of the DART Impact

Gene Fahnestock, Derek C. Richardson, Andy Cheng, and the Dynamical and Physical Properties Working Group of the DART Investigation Team

July 20, 2018

NASA
Goddard Space Flight Center
Johnson Space Center
Langley Research Center
Glenn Research Center
Marshall Space Flight Center
Planetary Defense Coordination Office

APL Johns Hopkins Applied Physics Laboratory

Jet Propulsion Laboratory
California Institute of Technology

University of Colorado Boulder

University of Maryland

Lawrence Livermore National Laboratory

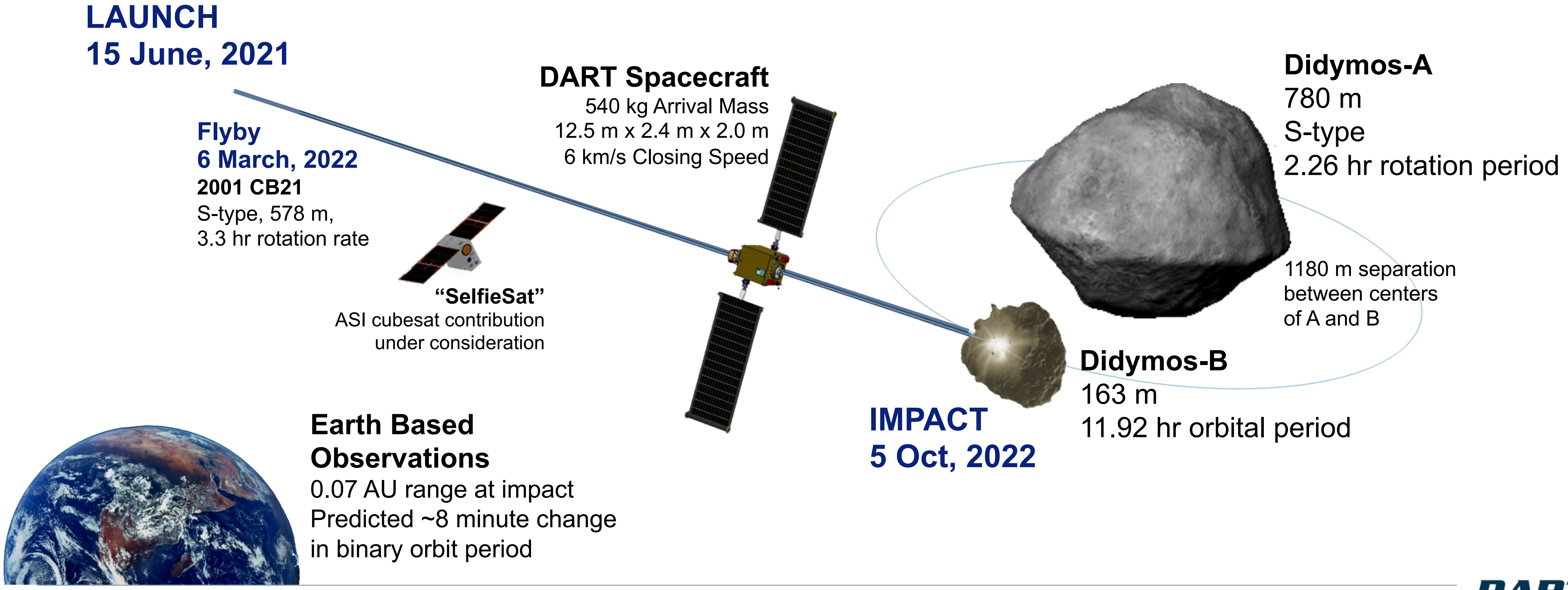
Aerojet Rocketdyne

Double Asteroid Redirection Test (DART)

- Designed to be first *meaningful* demonstration of kinetic impactor
- Target the binary NEA system 65803 Didymos (1996 GT)
- Impact Didymos-B and change the period of mutual orbit
- Measure the period change from Earth-based assets

Recent Mission Milestones:

- DART Investigation Team Meeting held: 9 April, 2018
- PDR completed: 10–12 April, 2018
- KDP-C: 10 July, 2018



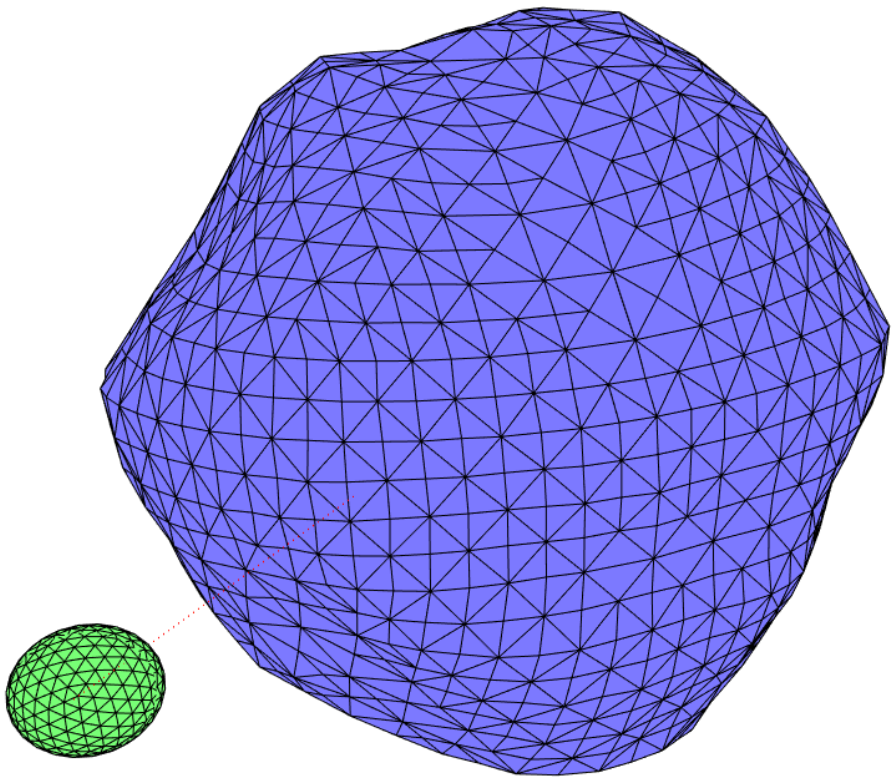
Dynamical & Physical Properties Working Group

Many Ongoing Studies with these Objectives:

1) **Characterizing the Didymos system's pre-impact dynamics, and un-perturbed and perturbed time evolution thereof, consistent with all observation data**

2) **Modeling changes to the system's dynamics that may be induced by the DART spacecraft's impact**

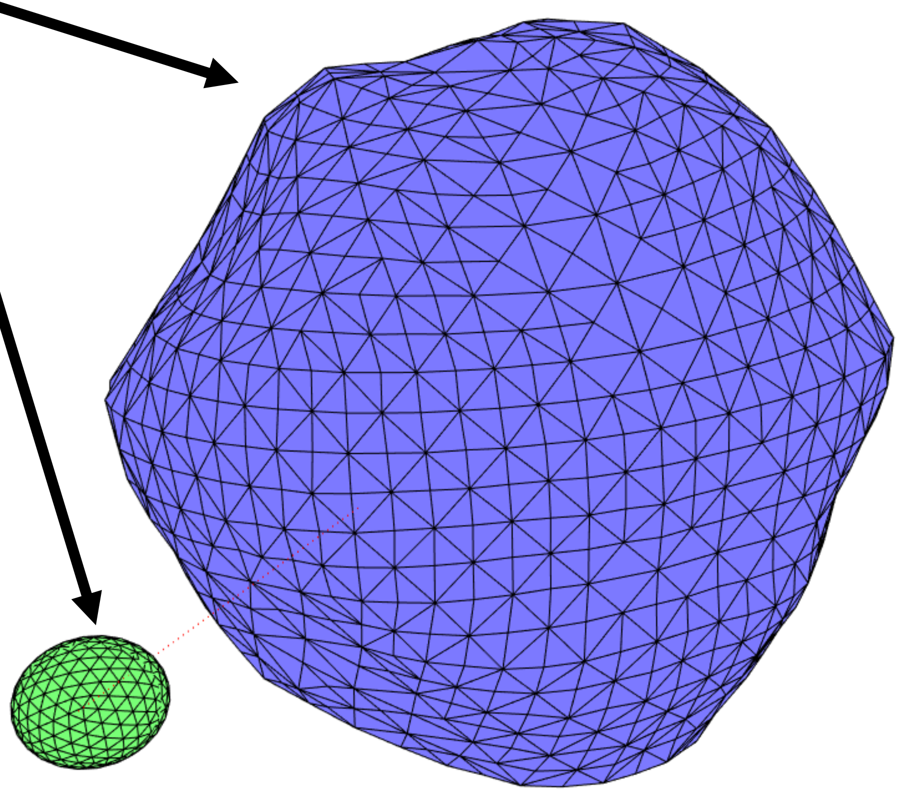
3) **Determining how physical properties can be inferred based on current knowledge**



Didymos Reference Model (DRM)

Key Features of System

- **Radar and light curve derived primary shape model**
- **Can only assume axial ratios for elongated ellipsoidal secondary ($a_s > b_s > c_s$; $a_s/b_s = 1.3 \pm 0.2$; $b_s/c_s = 1.2$)**
  - **available data don't support getting secondary shape**
- **Primary rotation period and binary orbit period well constrained from photometric light curve data**
- **From mean separation and orbit period, get system mass**
- **Individual component masses not yet distinguished!**
- **Derived bulk density (assumed common) has large uncertainty**
- **Assume on-average synchronous rotation of secondary**
- **Assume near-alignment of both body spin poles with orbit pole**



Didymos Reference Model (DRM)

Key Features of System

Parameter	Value	Parameter	Value
Primary rotation period	2.2600 ± 0.0001 hr	Bulk density, ρ	2104 kg/m³ ±30%
Mutual orbit period	$11.920 + 0.004/{-0.006}$ hr	System absolute magnitude, H	18.16 ± 0.04
Mean separation, a_{orb}	$1.18 \ + 0.04/{-0.02}$ km	Geometric albedo	0.15 ± 0.04
Total system mass	$5.278e11 \pm 0.54e11$ kg	Radar albedo	$0.27 \pm 25\%$
Diameter ratio, D_S/D_P	0.21 ± 0.01	Mutual orbit eccentricity	$e \leq 0.03$
Primary Diameter, D_P	780 m $\pm$ 10%	Mutual orbit pole (ecliptic lon.)	$\lambda = 310°$
Secondary Diameter, D_S	163 ± 18 m	Mutual orbit pole (ecliptic lat.)	$\beta = -84°$

Note: Observations planned for March 2019 apparition should, if successful, eliminate current uncertainty about secondary elongation, and establish (so far assumed) synchronous rotation of secondary

Didymos Reference Model (DRM)

Key Features of System

Parameter	Value	Parameter	Value
Primary rotation period	2.2601 ± 0.0001 hr	Bulk density, ρ	2104 kg/m³ ±30%
Mutual orbit period	11.92164 ± 0.00003 hr **	System absolute magnitude, H	18.16 ± 0.04
Mean separation, a_{orb}	$1.18\ +0.04/-0.02$ km	Geometric albedo	0.15 ± 0.04
Total system mass	$5.278e11 \pm 0.54e11$ kg	Radar albedo	$0.27 \pm 25\%$
Diameter ratio, D_S/D_P	0.21 ± 0.01	Mutual orbit eccentricity	$e \leq 0.03$
Primary Diameter, D_P	780 m $\pm$ 10%	Mutual orbit pole (ecliptic lon.)	$\lambda = 270°$
Secondary Diameter, D_S	163 ± 18 m	Mutual orbit pole (ecliptic lat.)	$\beta = -87°$

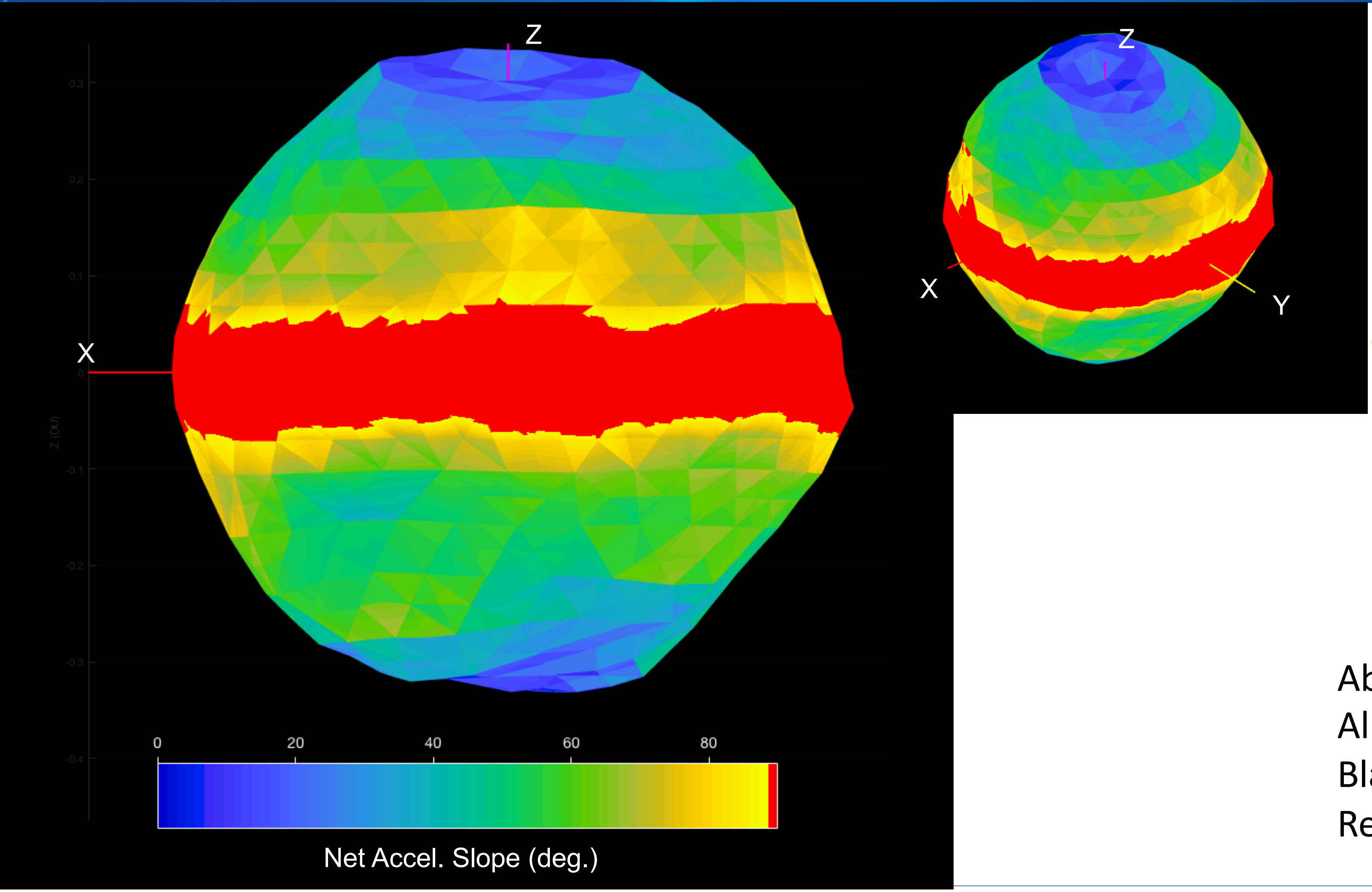
Recent changes suggested at June 2018 Didymos Observers workshop in Prague

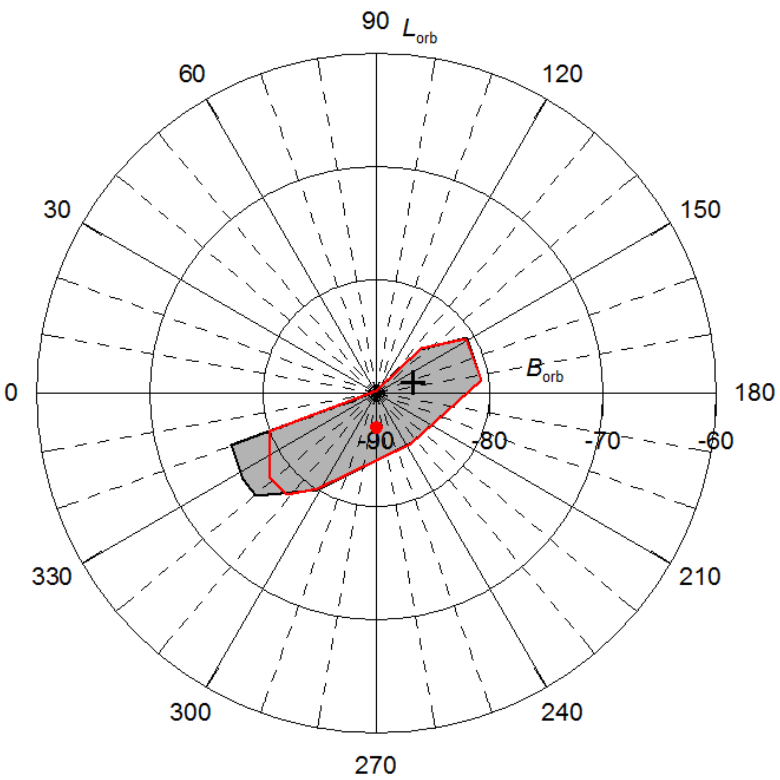
** Assuming zero BYORP! But 5 possible BYORP ΔM solutions exist, one of them consistent with zero, and 2019 + 2020/2021 apparition observations should be capable of distinguishing between them!

DART
Double Asteroid Redirection Test

Primary Near Spin Disruption Limit?

Local Acceleration Slope on Primary Surface, assuming DRM nominal values:





Above:
Allowed conservative 3-σ uncertainty plotted
Black outline: 2003+2015 data
Red outline: 2003+2015+2017 data

DART Double Asteroid Redirection Test

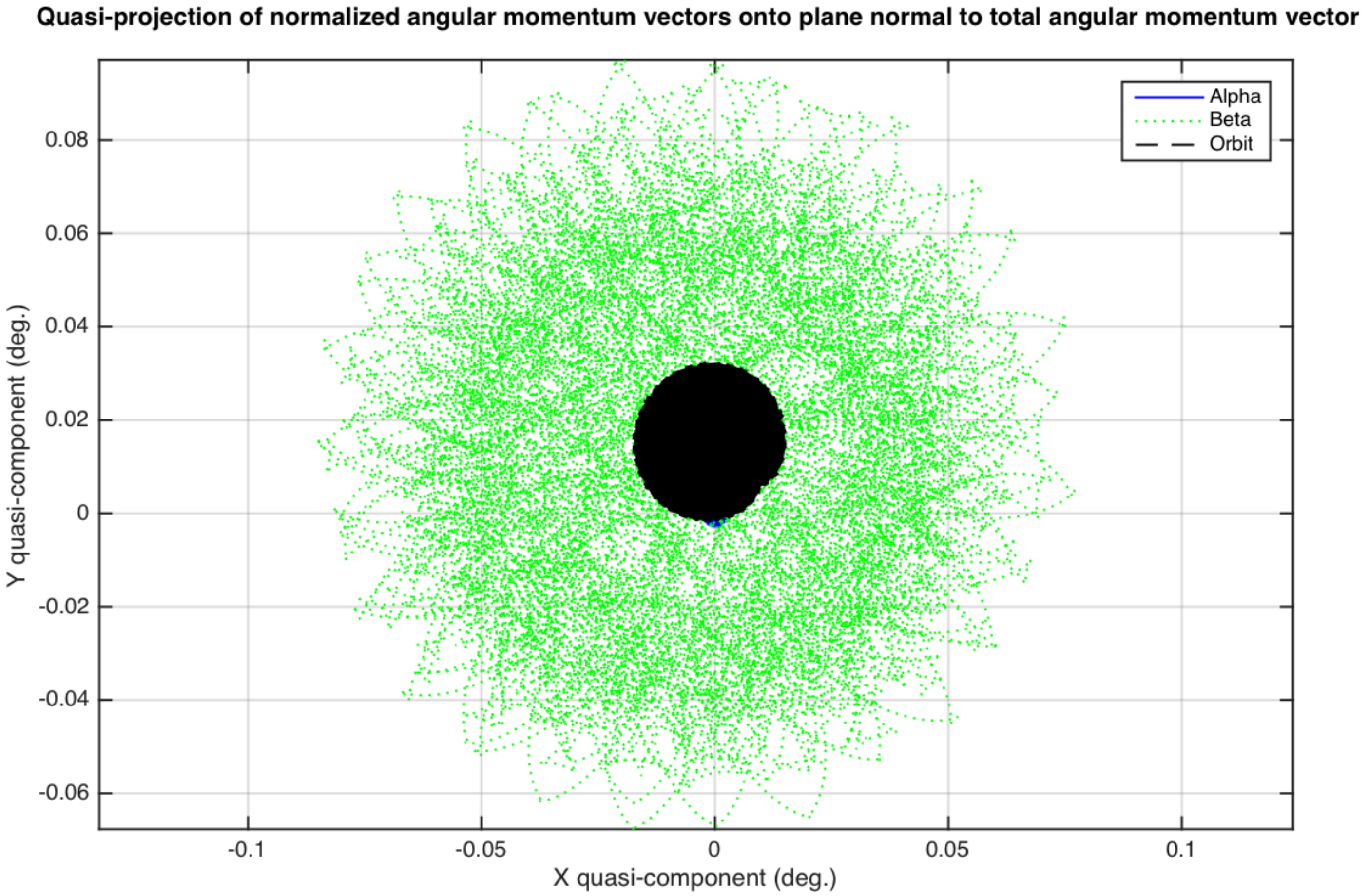
Long-Term Time Evolution of Pre-Impact Dynamics

Effects Examined

- **External tides from Sun and Planets**
- **Solar radiation pressure**
- **Thermal re-radiation (B-YORP)**
- **Inter-component tidal energy dissipation**

High-Fidelity F2BP Simulations over Shorter, Mission-Appropriate Durations

- **Example Didymos instantiations consistent with DRM**
- **Observe expected modes of motion:**
  - **Body spin and orbit angular momenta vectors co-precession**



DART Double Asteroid Redirection Test

High-Fidelity F2BP Simulations over Shorter, Mission-Appropriate Durations

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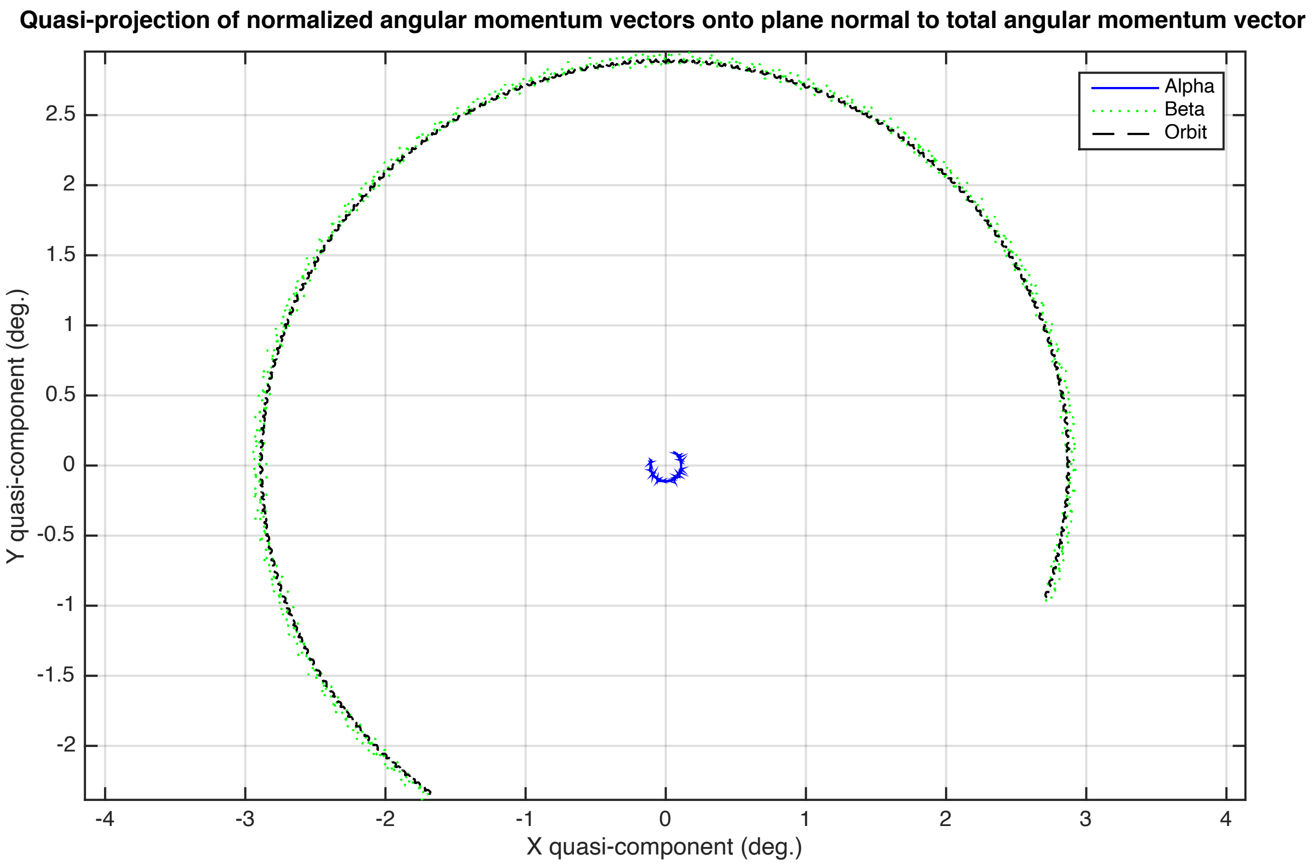

DART
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High-Fidelity F2BP Simulations over Shorter, Mission-Appropriate Durations

- **Example Didymos instantiations consistent with DRM**
- **Observe expected modes of motion:**
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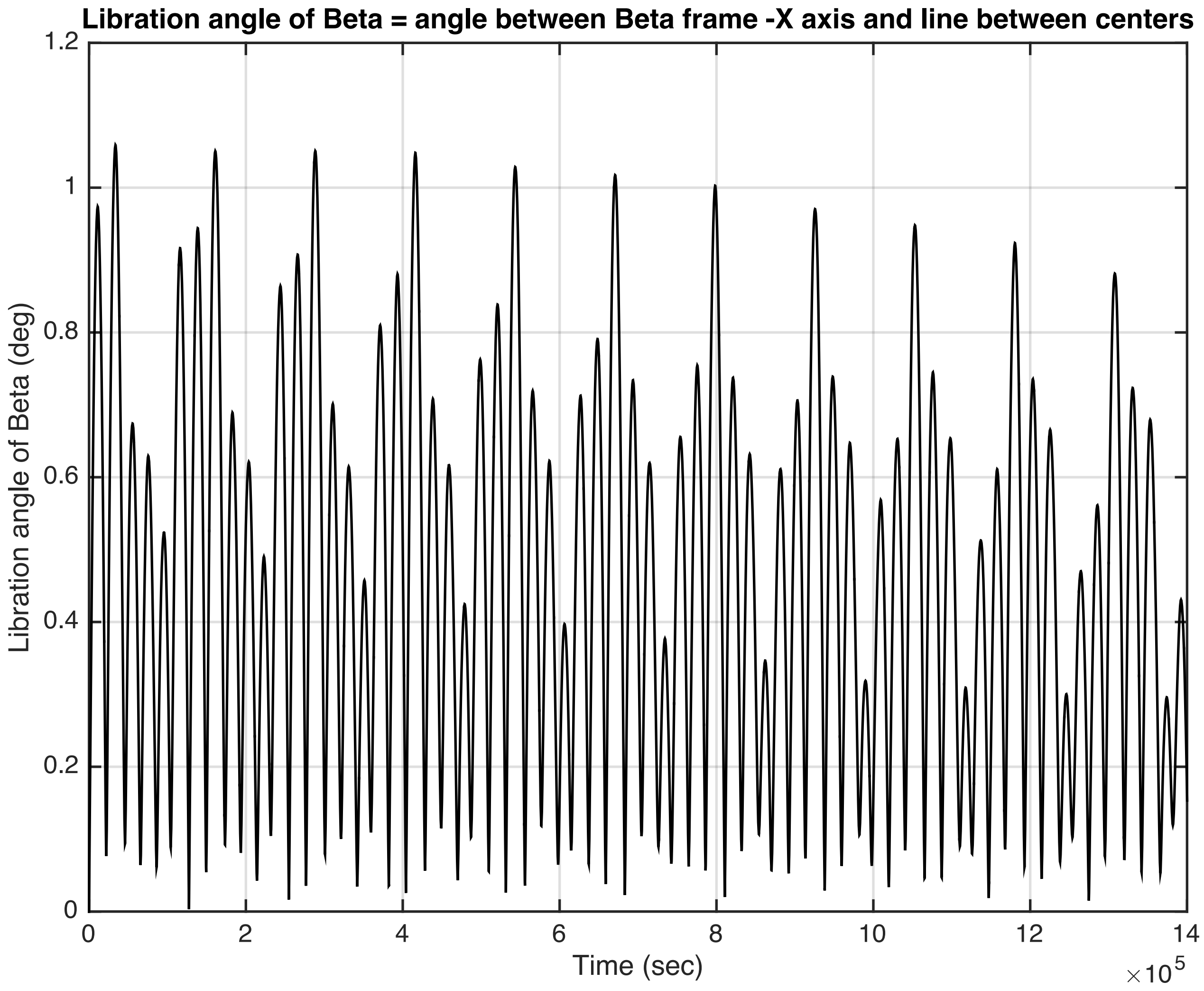
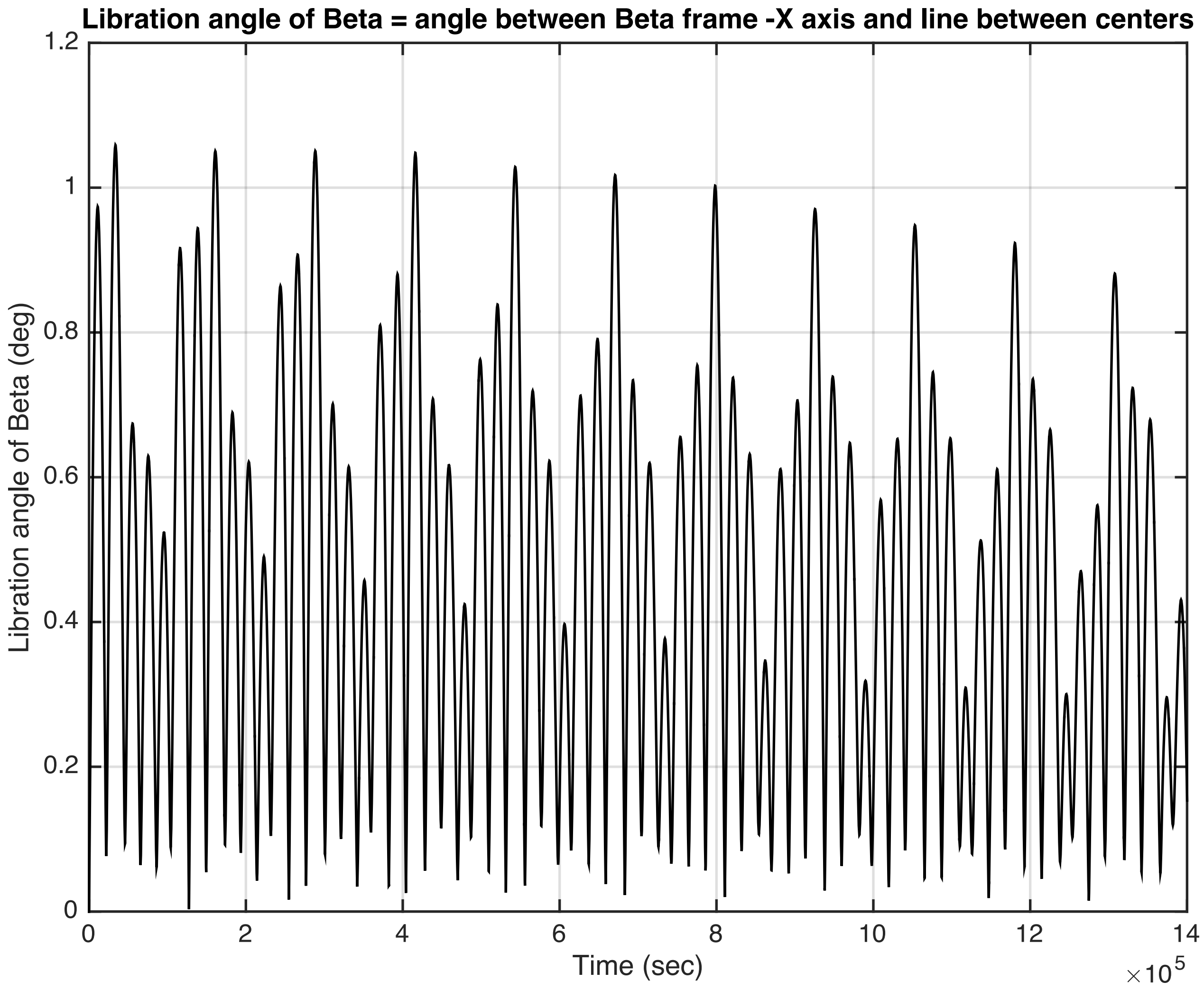
  - **Secondary libration**



High-Fidelity F2BP Simulations over Shorter, Mission-Appropriate Durations

- **Example Didymos instantiations consistent with DRM**
- **Observe expected modes of motion:**
  - **Body spin and orbit angular momenta vectors co-precession**
  - **Secondary libration**
- **Modes all expected to be as relaxed as possible pre-impact**
- **Minimum forced libration amplitude → dependent on mutual orbit eccentricity and choice of secondary shape**



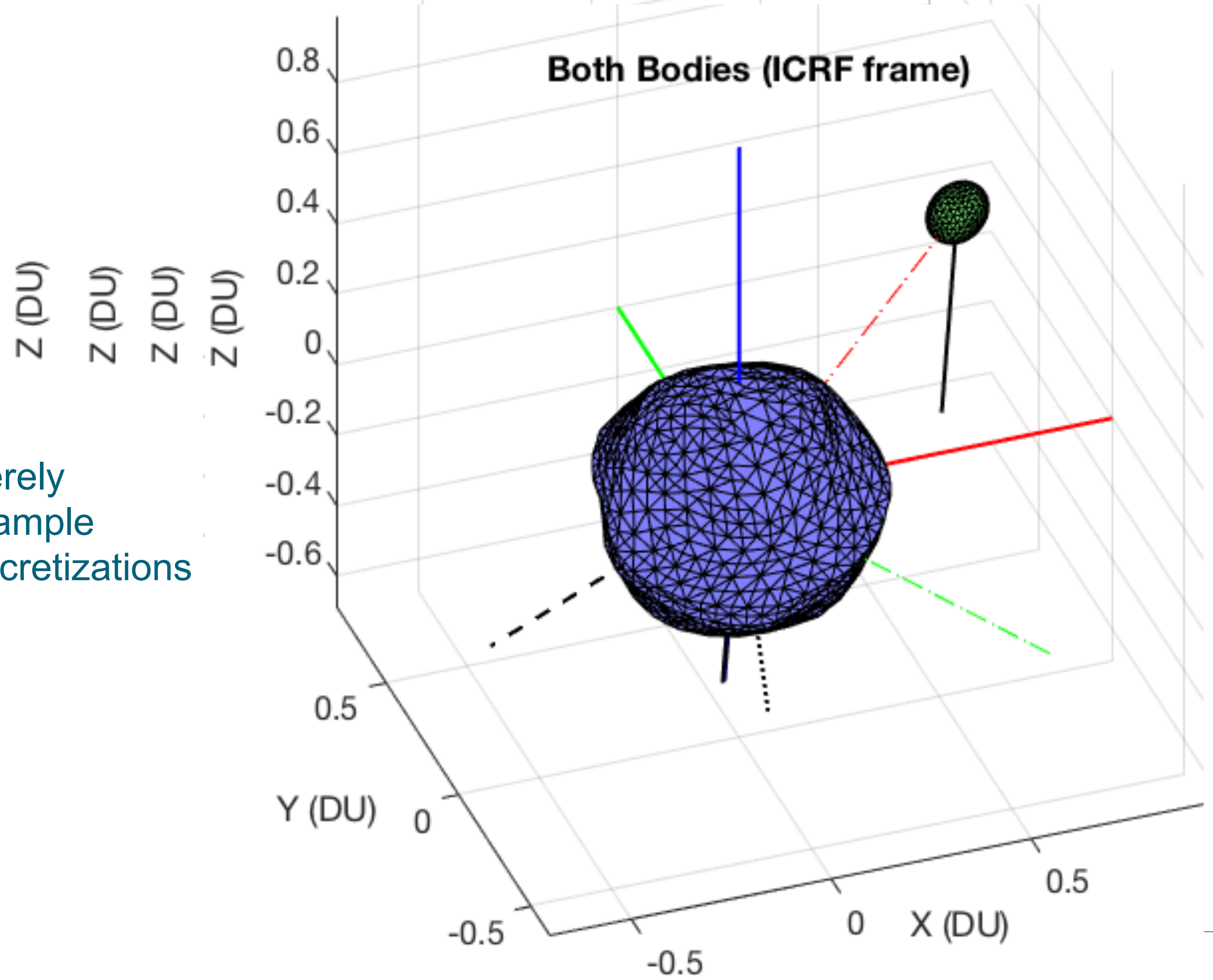
F2BP Simulation Benchmarking Exercise

Four Test Systems Used

- **Two Cubes**
  (V=8, F=12) x2
- **Two Spheres**
  (V=252, F=500) x2
- **Two Ellipsoids**
  (V=252, F=500) x2
- **Didymain shape model + Ellipsoid**
  (V=1000, F=1996) x (V=252, F=500)

merely example discretizations

All systems are "Didymos-like"



DART Double Asteroid Redirection Test

F2BP Simulation Benchmarking Exercise

Participants, Methods

Group >>	JPL	GSFC	AU	UCB	UMD
Code description	mutual potential formulation for polyhedra, as in Werner & Scheeres 2005, relative coord.	mutual potential formulation for polyhedra, as in Werner & Scheeres 2005, inertial coord.	similar to JPL, except uses automatic, recursive order-coefficient calculator	mutual potential formulation using recursive expansion of inertia integrals, as in Hou 2016	pkdgrav, parallel N-body tree-code with mutual gravity potential, SSDEM if contact forces included
Approach to discretization of shape	tetrahedral simplex for each polymesh facet	tetrahedral simplex for each polymesh facet	tetrahedral simplex for each polymesh facet	polymesh used to pre-compute inertia integrals	body shapes packed with spheres
Free parameters / "knobs"	integration step size, order N of Legendre poly. series expansion	integration step size, but (same) N fixed at $N = 3$	integration step size, order N of Legendre poly. series expansion	integration step size, inertia integral expansion order N	integration step size, kd-tree opening angle, #/size of spheres

DART
Double Asteroid Redirection Test

F2BP Simulation Benchmarking Exercise

Participants, Methods (Cont'd)

Group >>	JPL	GSFC	AU	UCB	UMD
Scaling of computational cost	$O(n^2)$, $O(6^N)$	$O(n^2)$, $O(6^N)$	$O(n^2)$, $O(6^N)$	only up-front inertia integral calc. is $O(f(N))$	$O(n \log(n))$ with tree-code, $O(n^2)$ w/o using that
Representability of benchmarking models	Two Cubes = exact Two Spheres = approximate Two Ellipsoids = approximate Didymain + Ellipsoid = exact				approximate, except for Two Spheres (in theory)
Numerical integration scheme	2nd order LGVI, fixed step size = 40s, symplectic, variational, geometric	2nd order LGVI, fixed step size = 40s, symplectic, variational, geometric	???	RK4, fixed step size = 5s	symplectic 2nd order leap-frog integrator (fixed step =1.875, 15 s) + adaptive-step RK5
Computer implementation details	written in C, parallelized using MPI, on cluster	FORTRAN, parallelized using MPI, on cluster	C++, not parallelized, single machine	C++, not parallelized, on laptop	written in C, CPU parallelism using pthreads, cluster

Benchmarking Results

Computational Cost

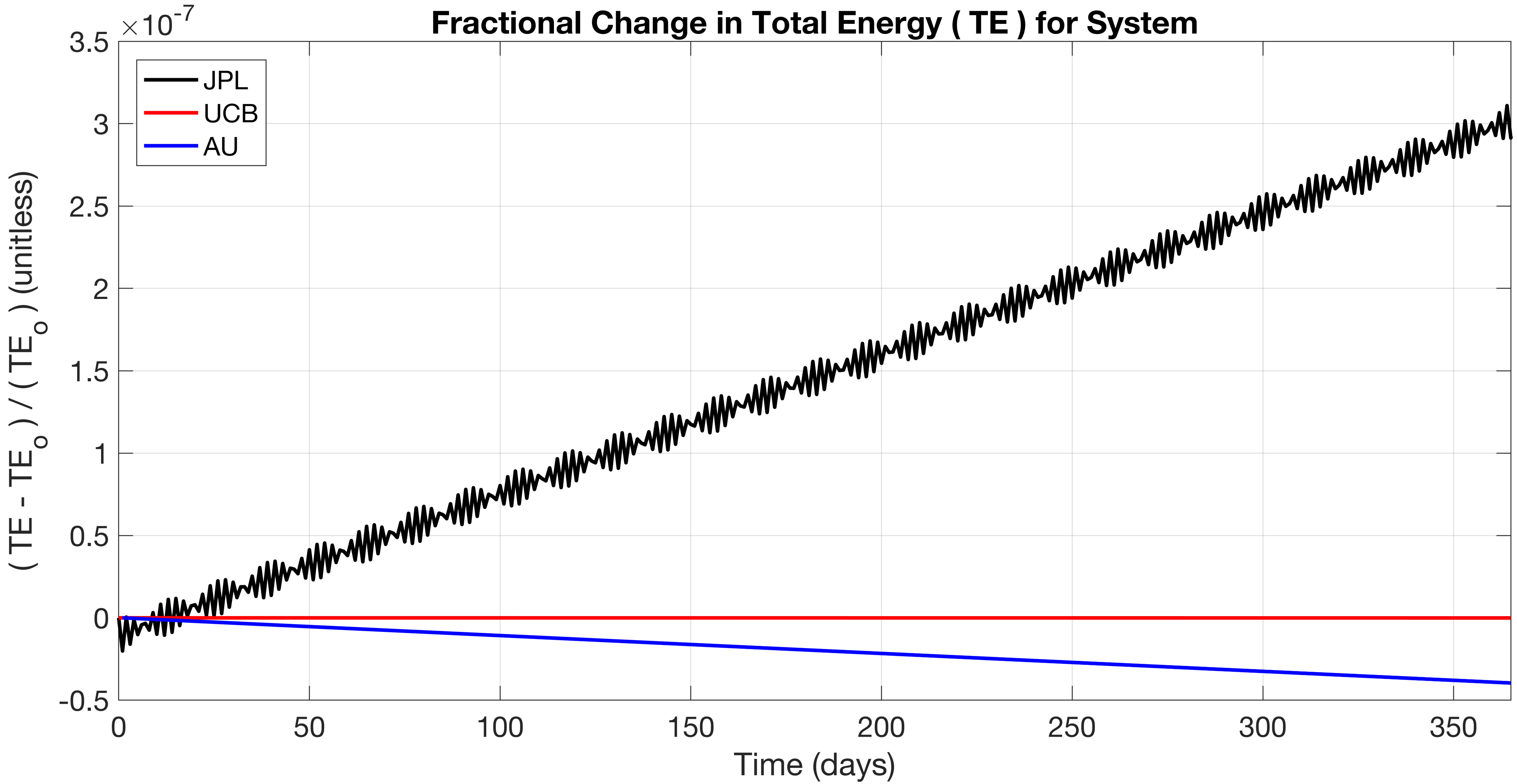
- **Sims run for 365+ days**
- **Sparse-time output every 1 day → leads to peak-shaving, under-sampling for fast angles (libration, etc.)**
- **Wall-time normalized by duration covered and multiplied by # of processors used = (proc*hrs)/day**

Participant	Model 1	Models 2 or 3	Model 4
JPL	~0.017	~3.351	~12.104
UCB	~0.466	~0.466	~0.466
GSFC	~0.081	~5.446	~20.288
UMD	--	--	~4.395 , 0.592 *
AU	~0.398 – 0.411	--	--

KEY:
Gravity Order N=3
Gravity Order N=4
∞ Gravity order, but discretization error

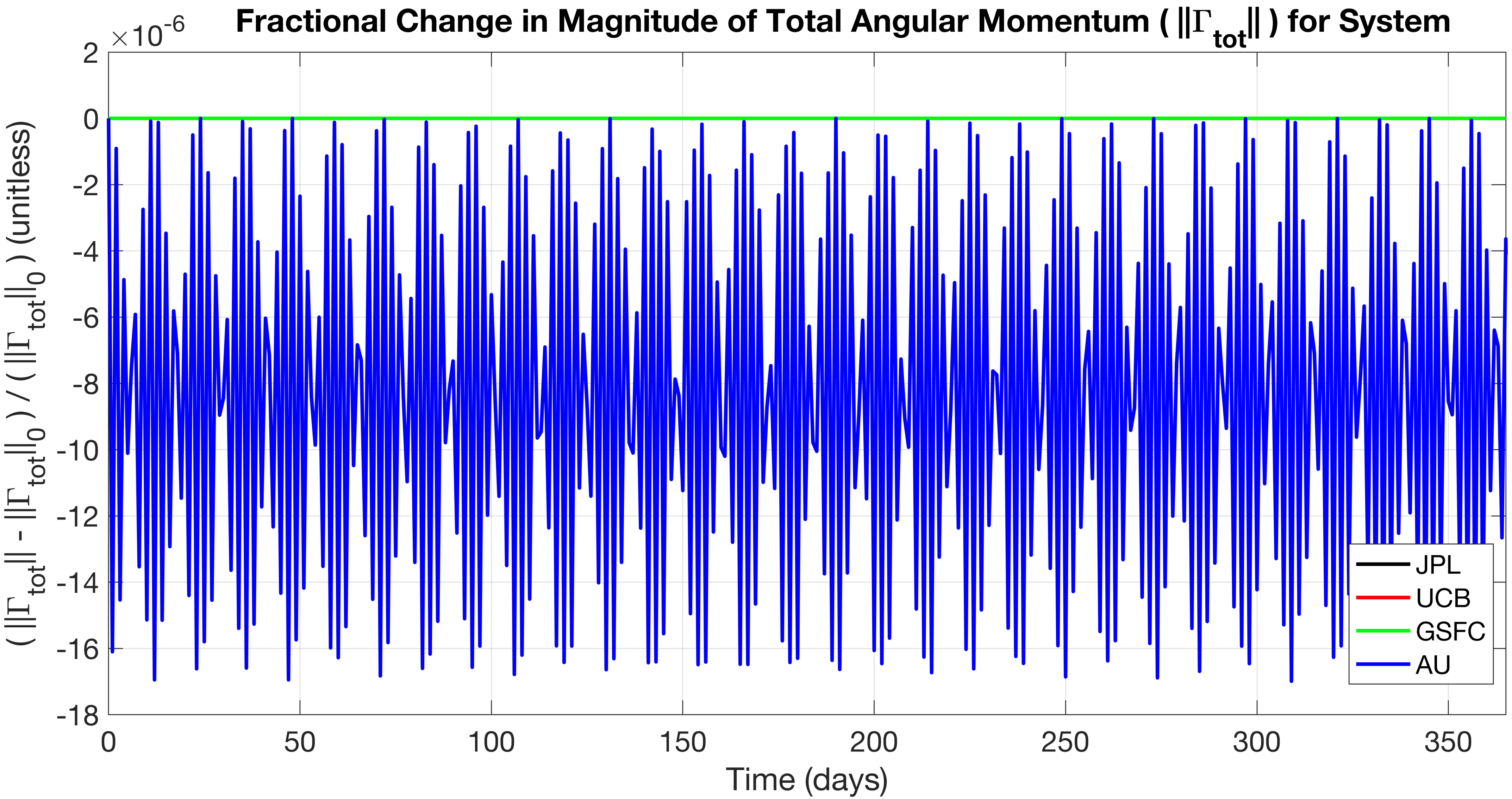
Benchmarking Results – Two Cubes

Growth in Fractional Error for Conserved Quantities



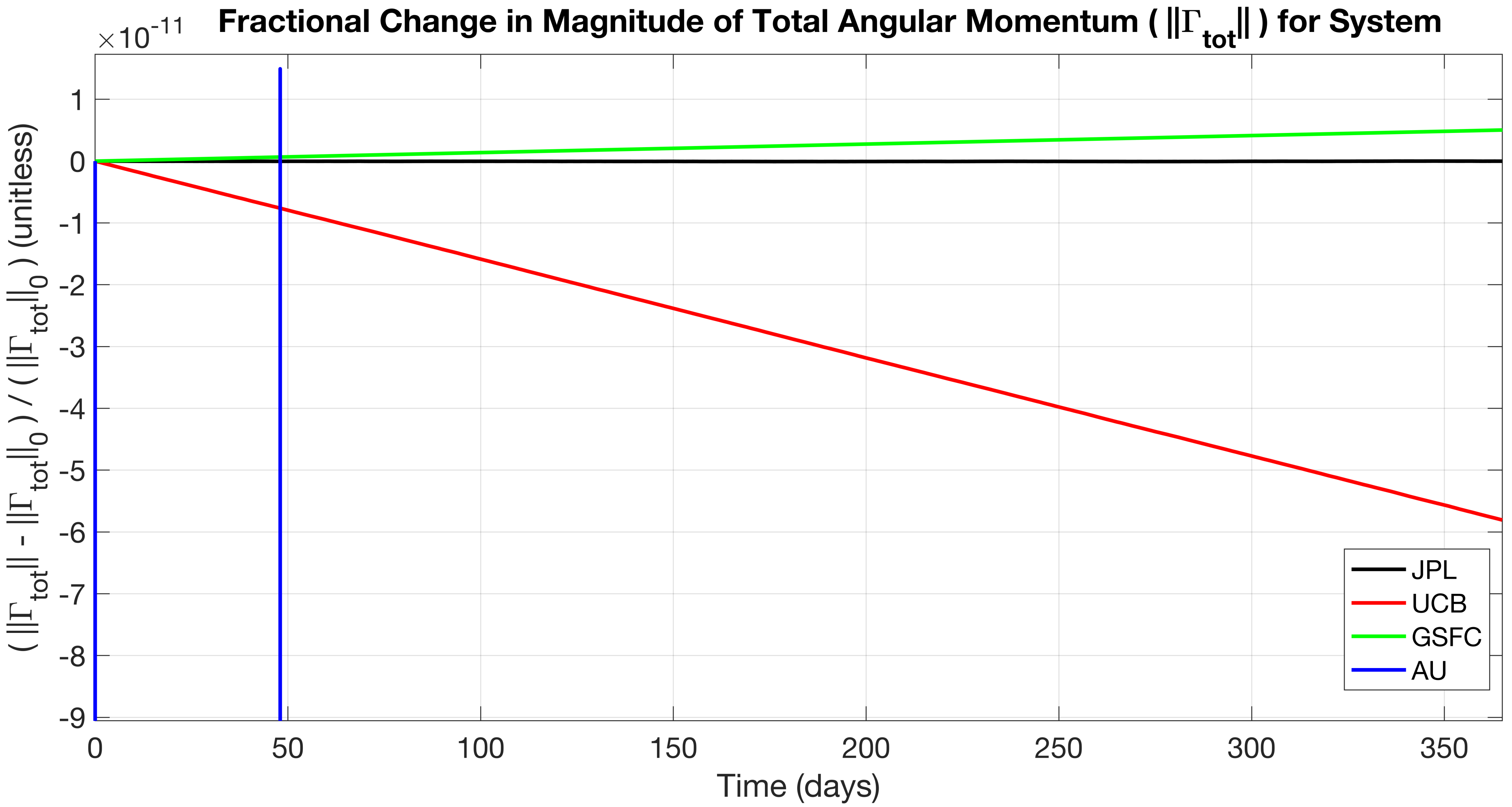
Benchmarking Results – Two Cubes

Growth in Fractional Error for Conserved Quantities



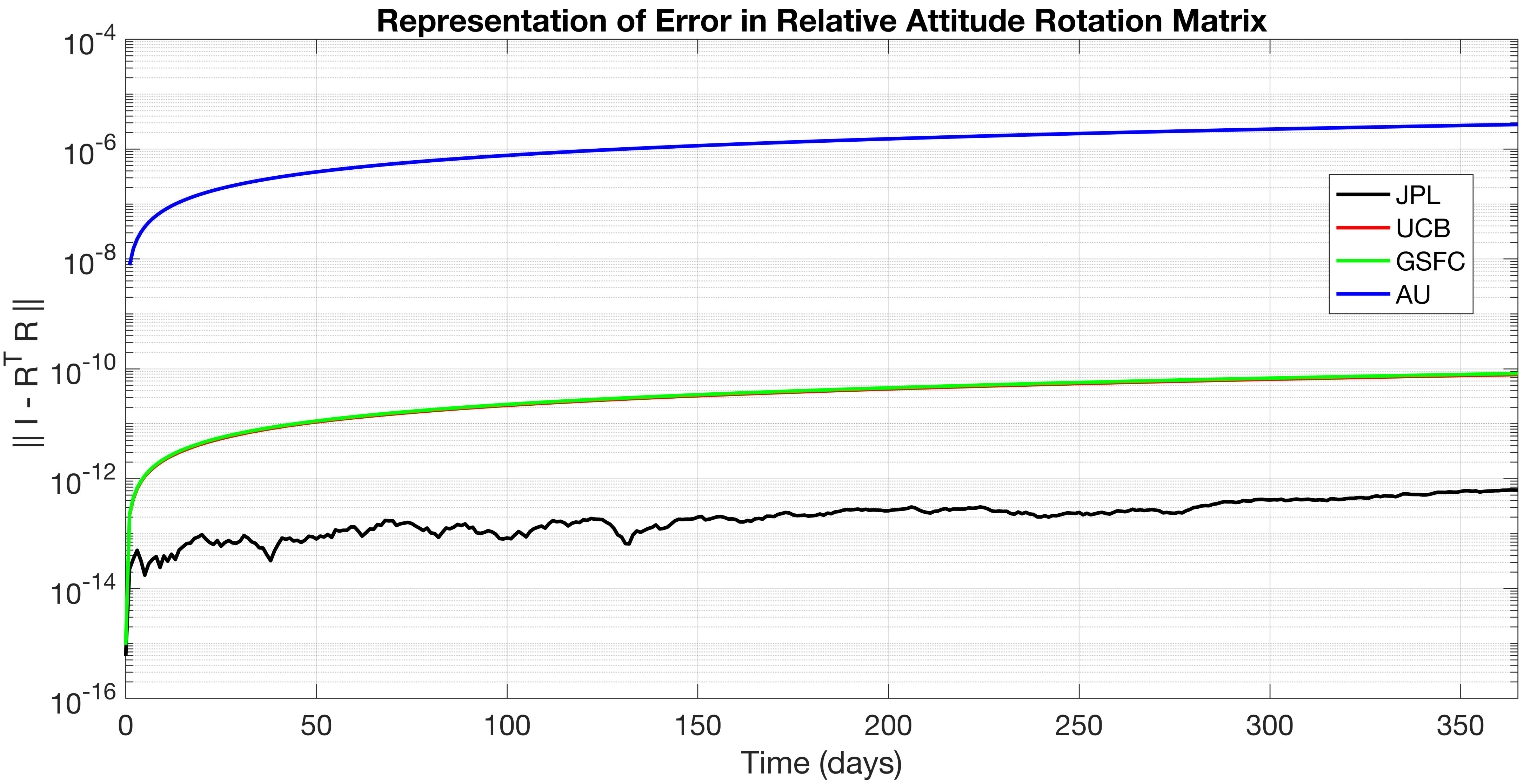
Benchmarking Results – Two Cubes

Growth in Fractional Error for Conserved Quantities



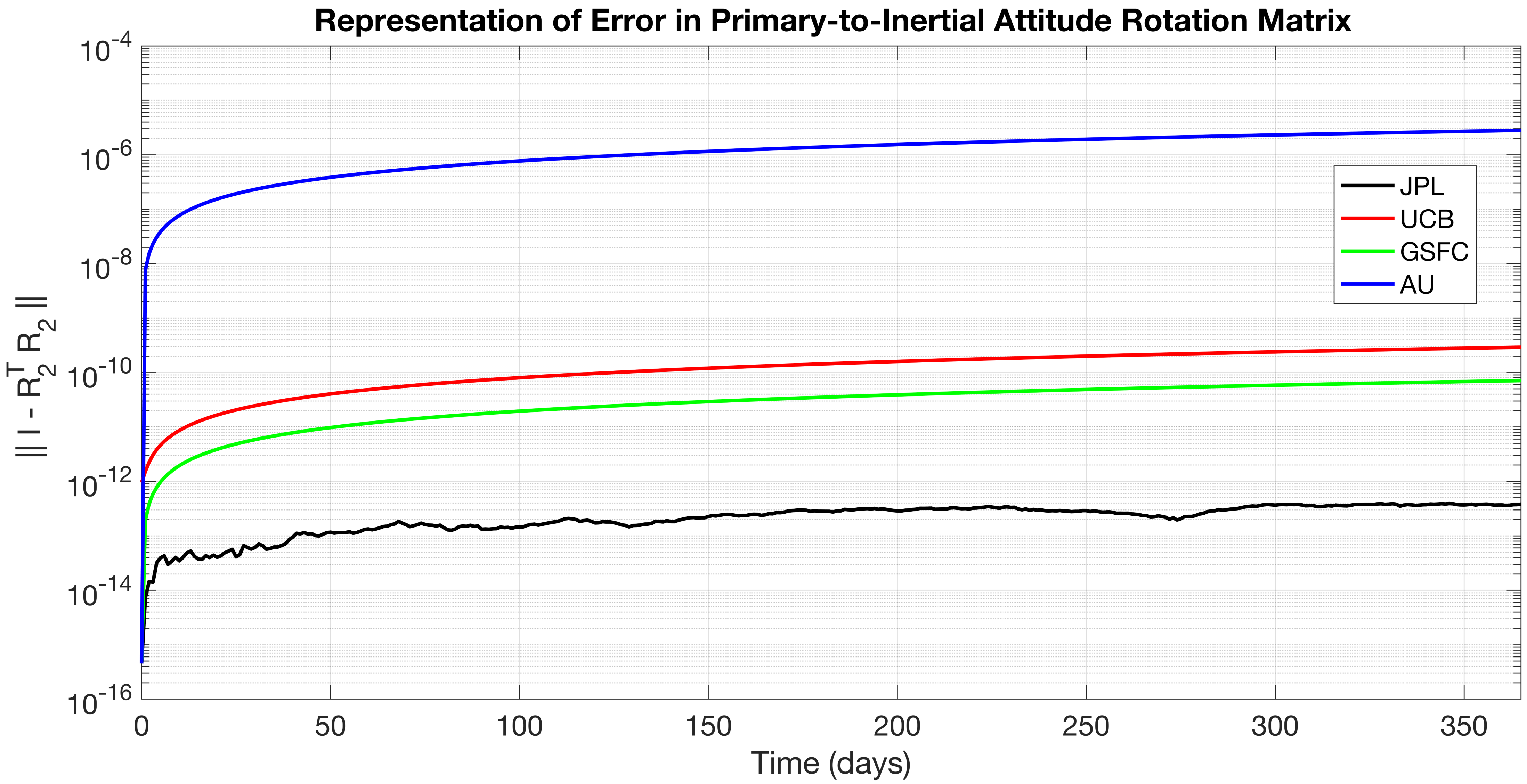
Benchmarking Results – Two Cubes

Divergence of attitude from SO(3) group, the geometry of rotational dynamics



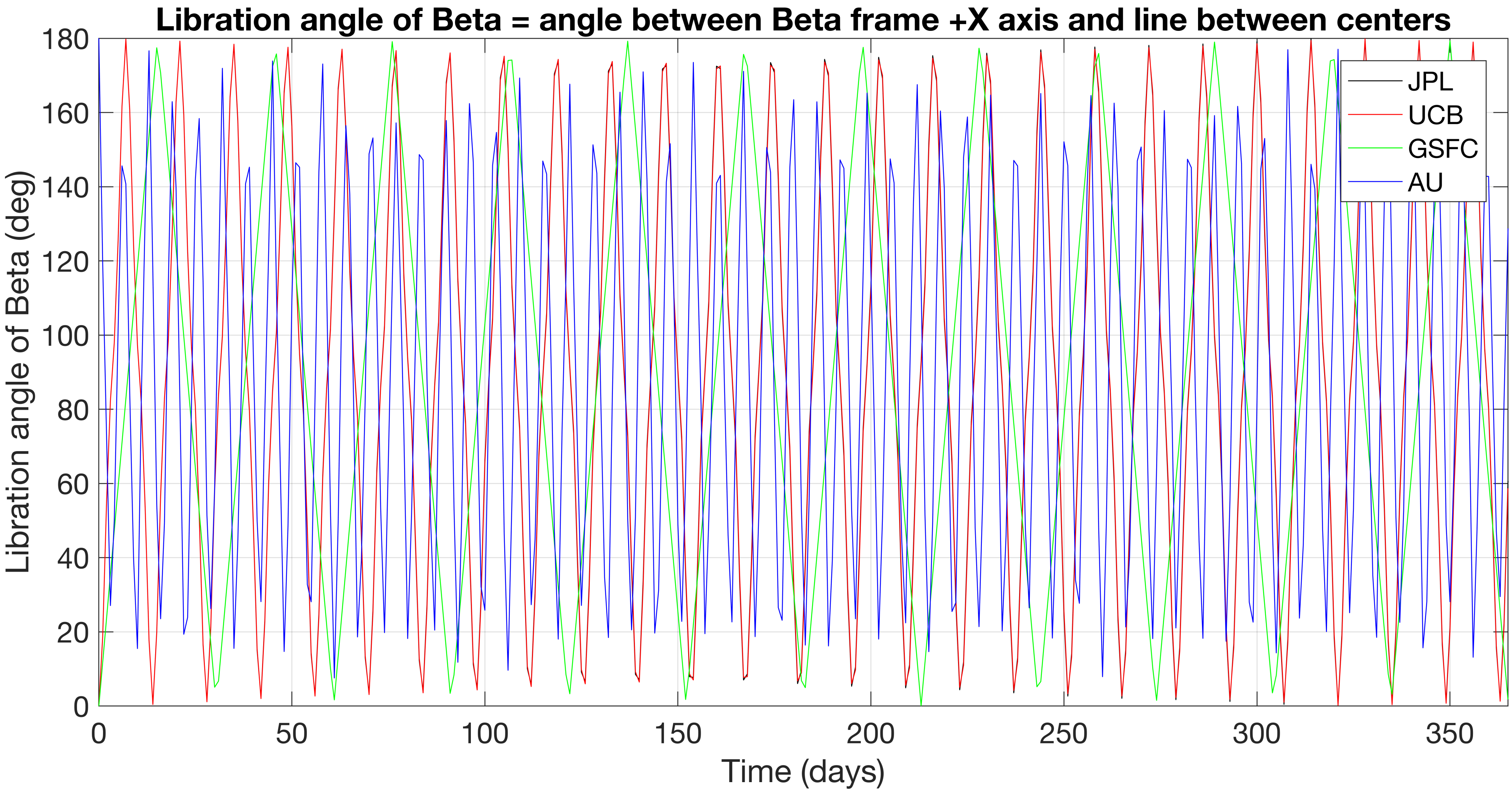
Benchmarking Results – Two Cubes

Divergence of attitude from SO(3) group, the geometry of rotational dynamics



Benchmarking Results – Two Cubes

Secondary's initial angular velocity deviation from synchronous → non-lock, circulation



Benchmarking Results – Two Cubes

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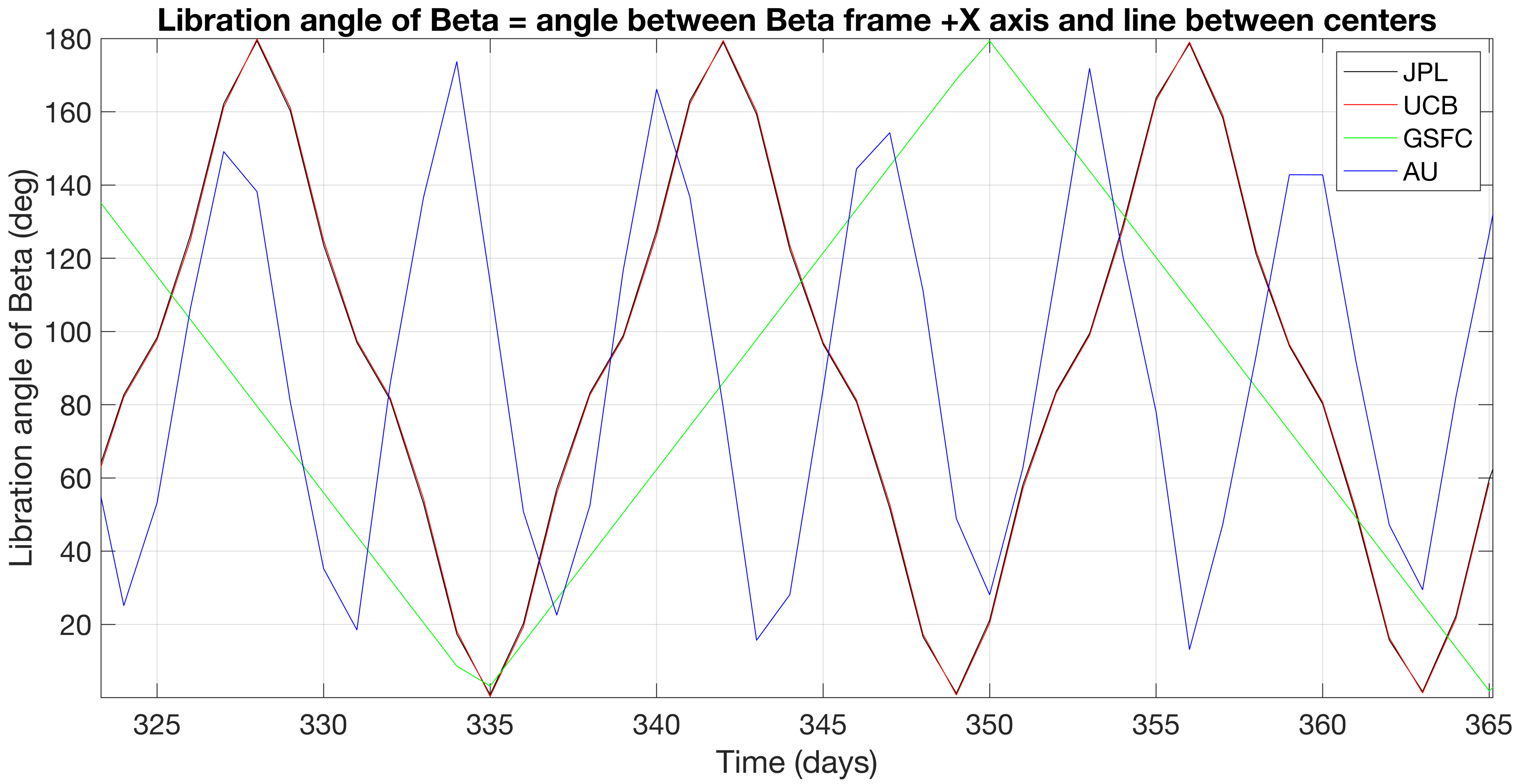
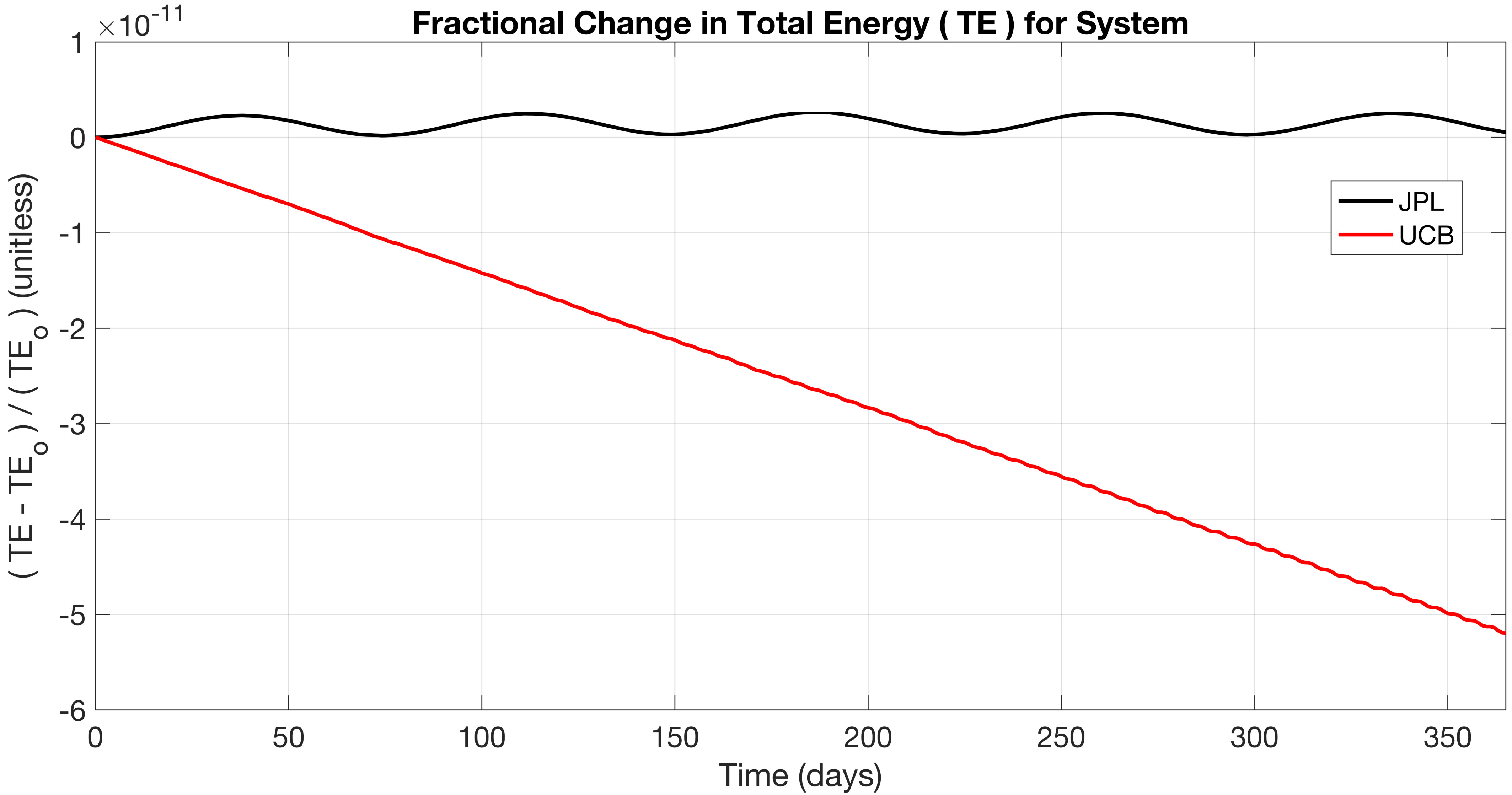


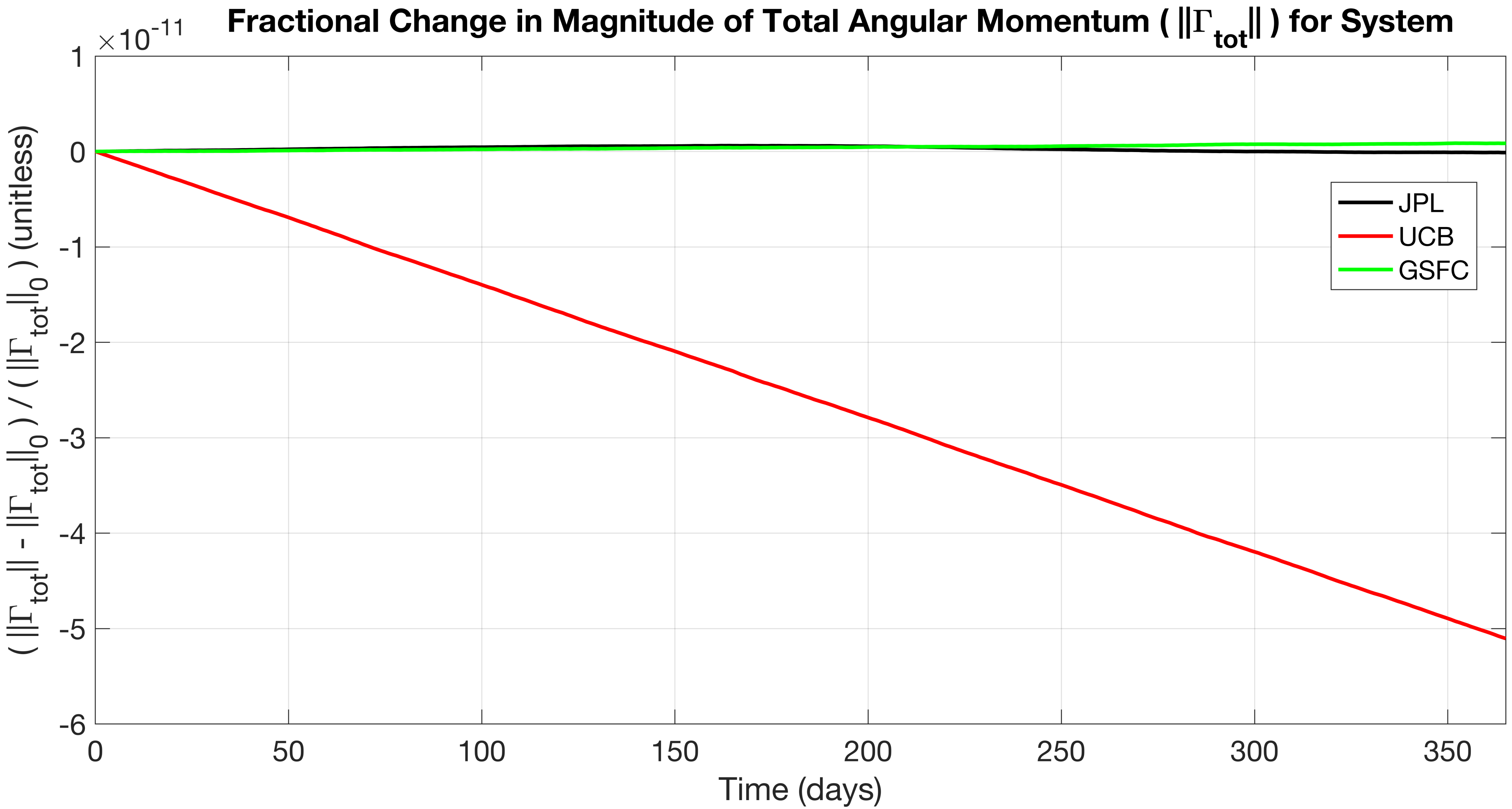
Benchmarking Results – Two Spheres

Growth in Fractional Error for Conserved Quantities



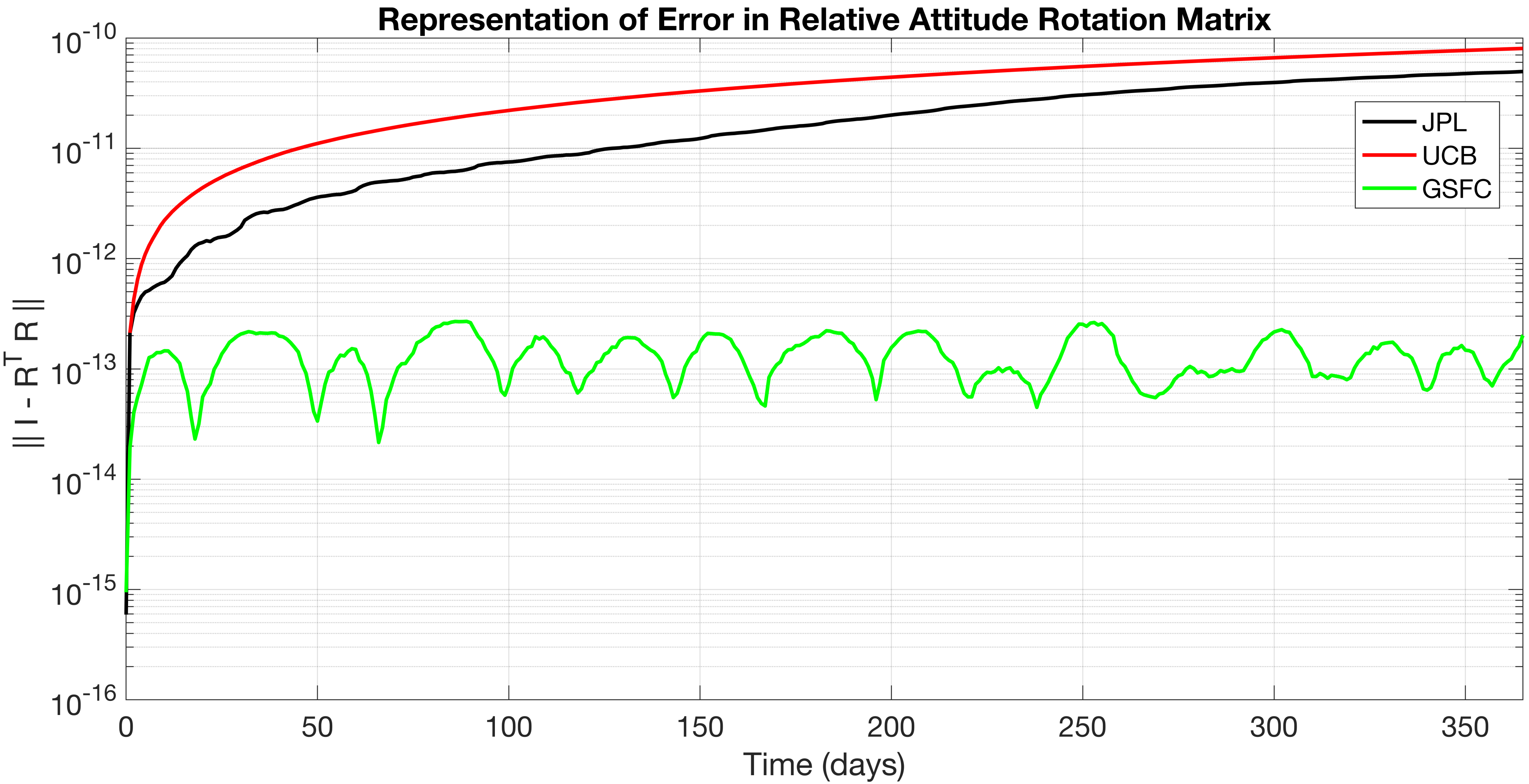
Benchmarking Results – Two Spheres

Growth in Fractional Error for Conserved Quantities



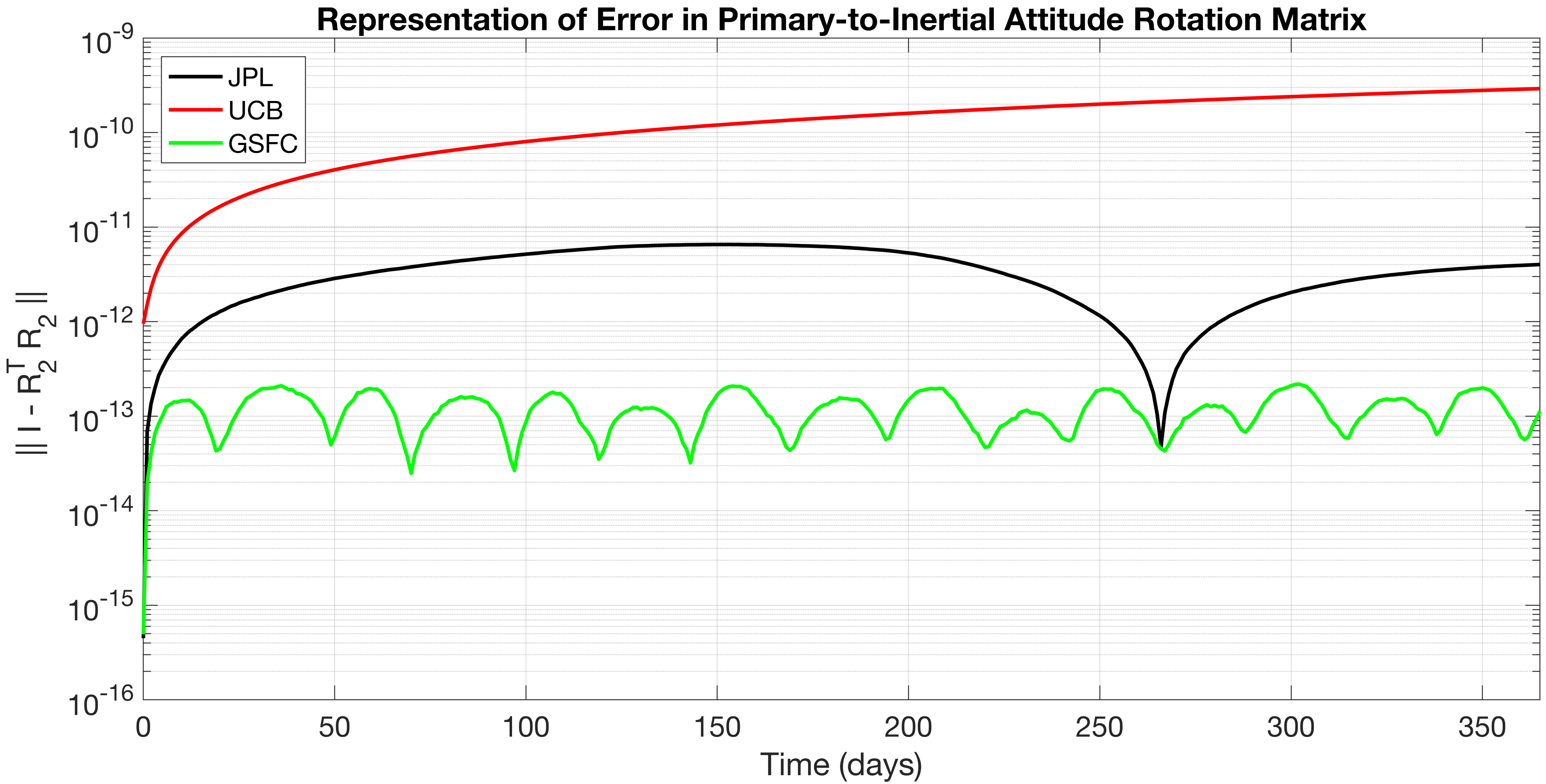
Benchmarking Results – Two Spheres

Divergence of attitude from SO(3) group, the geometry of rotational dynamics



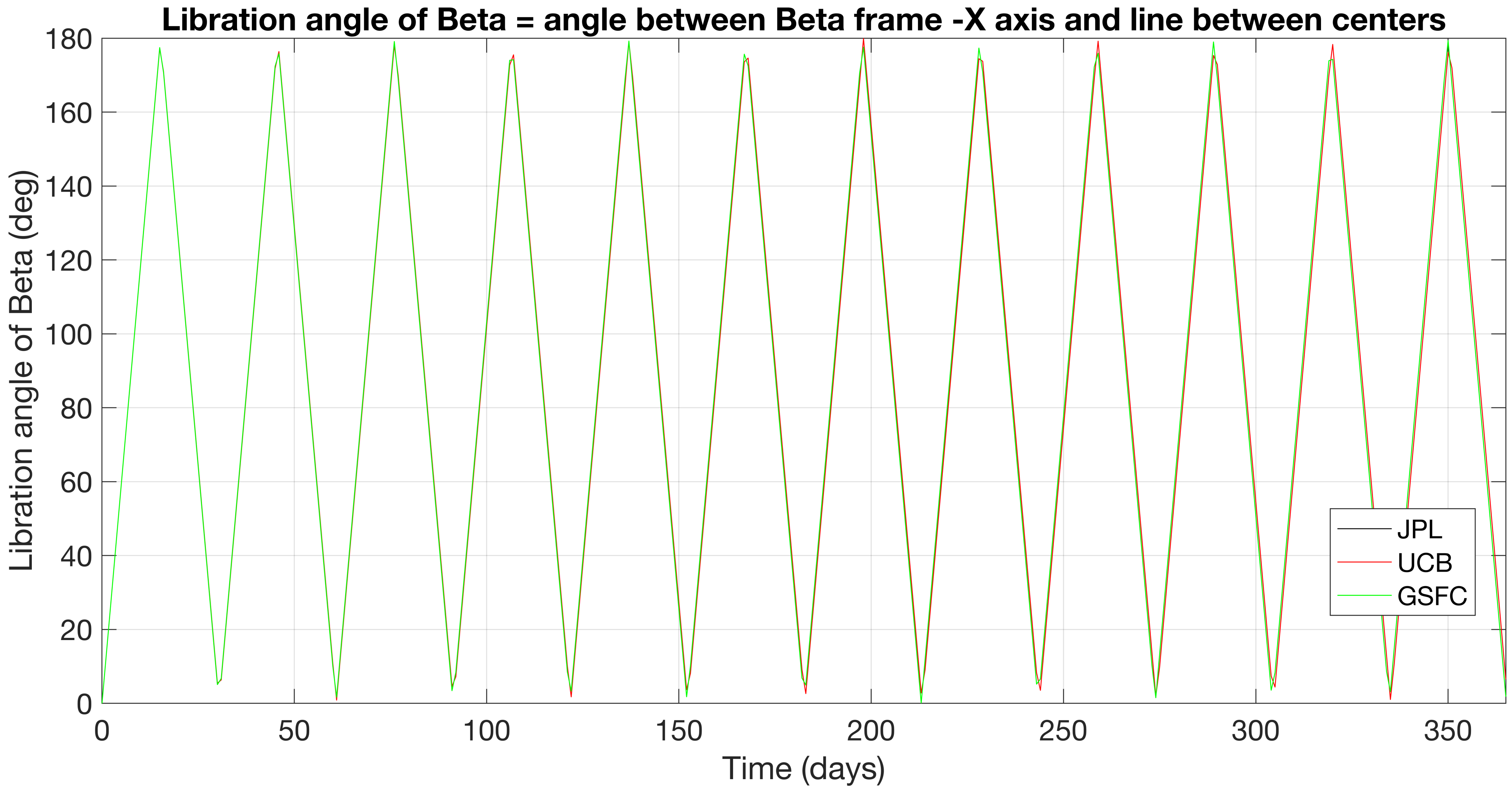
Benchmarking Results – Two Spheres

Divergence of attitude from SO(3) group, the geometry of rotational dynamics



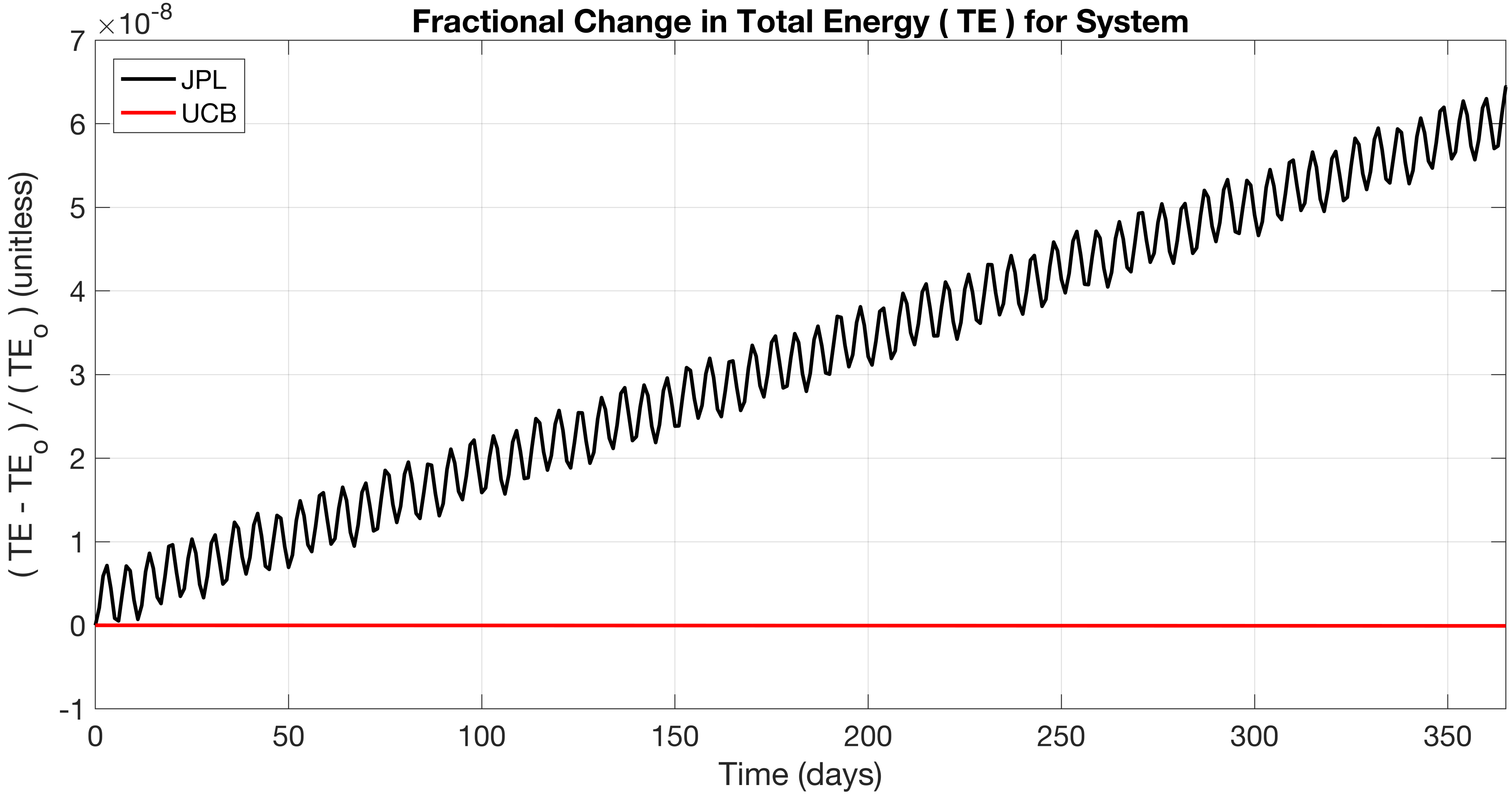
Benchmarking Results – Two Spheres

Secondary's initial angular velocity deviation from synchronous → non-lock, circulation



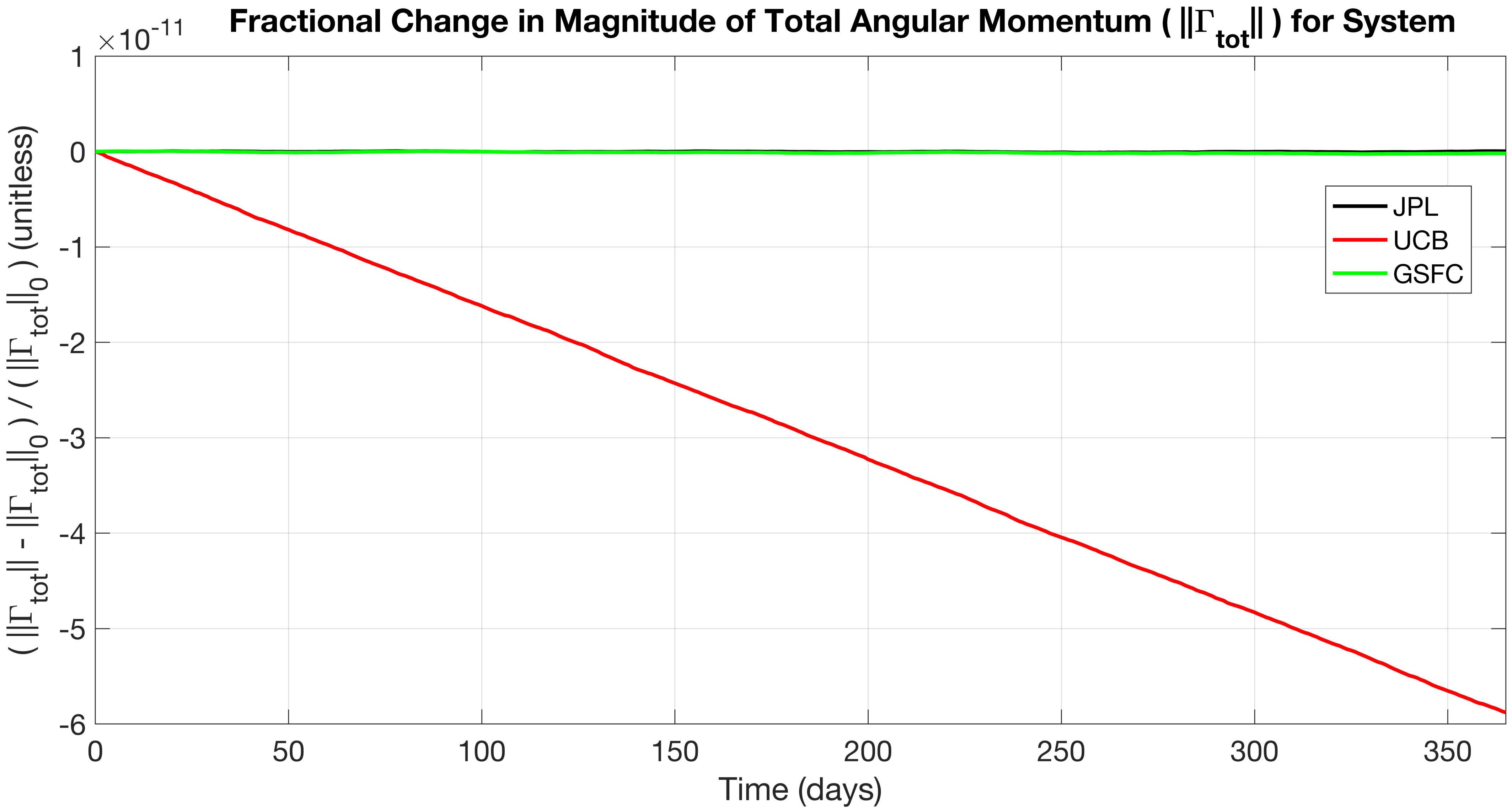
Benchmarking Results – Two Ellipsoids

Growth in Fractional Error for Conserved Quantities



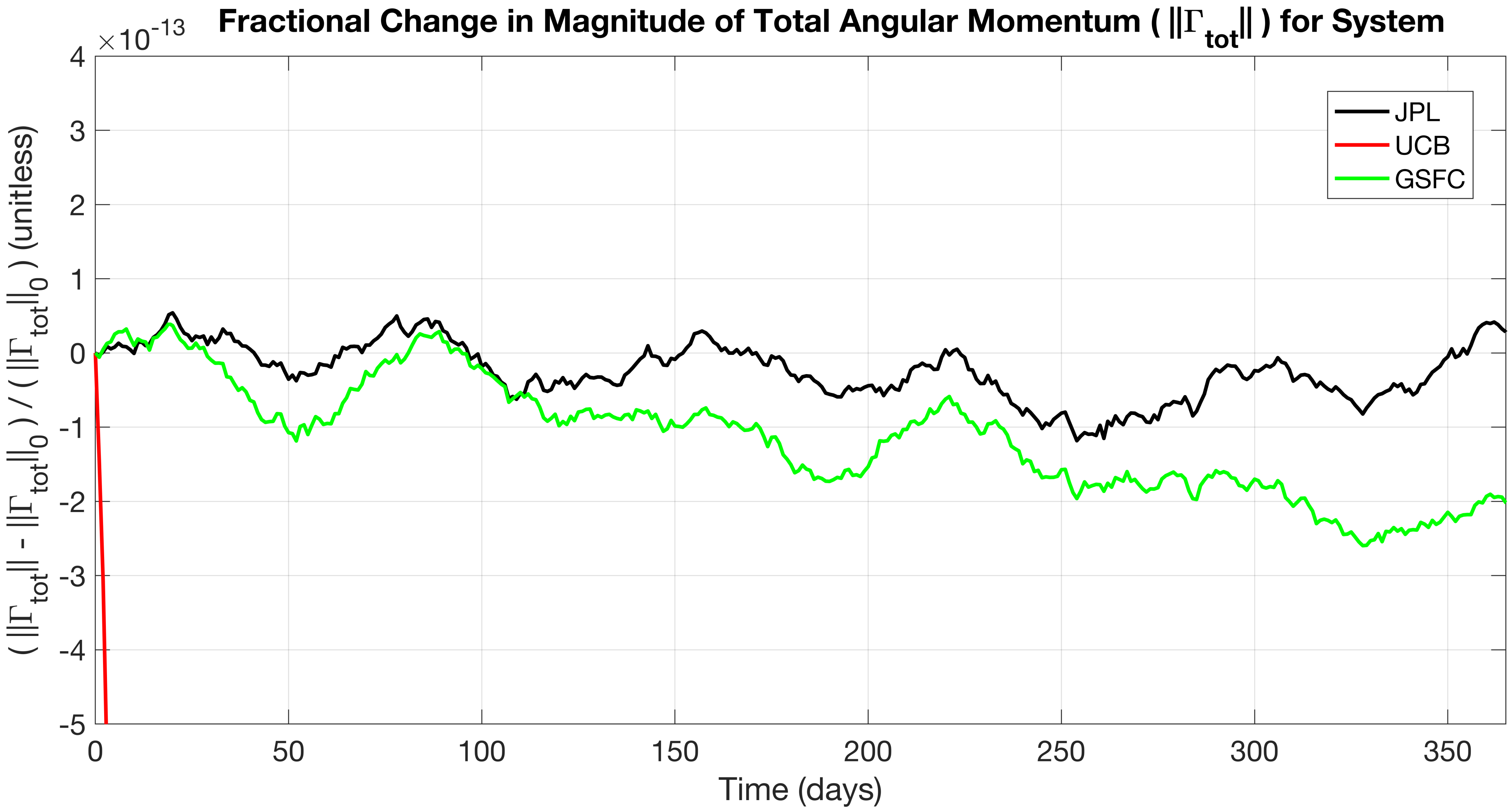
Benchmarking Results – Two Ellipsoids

Growth in Fractional Error for Conserved Quantities



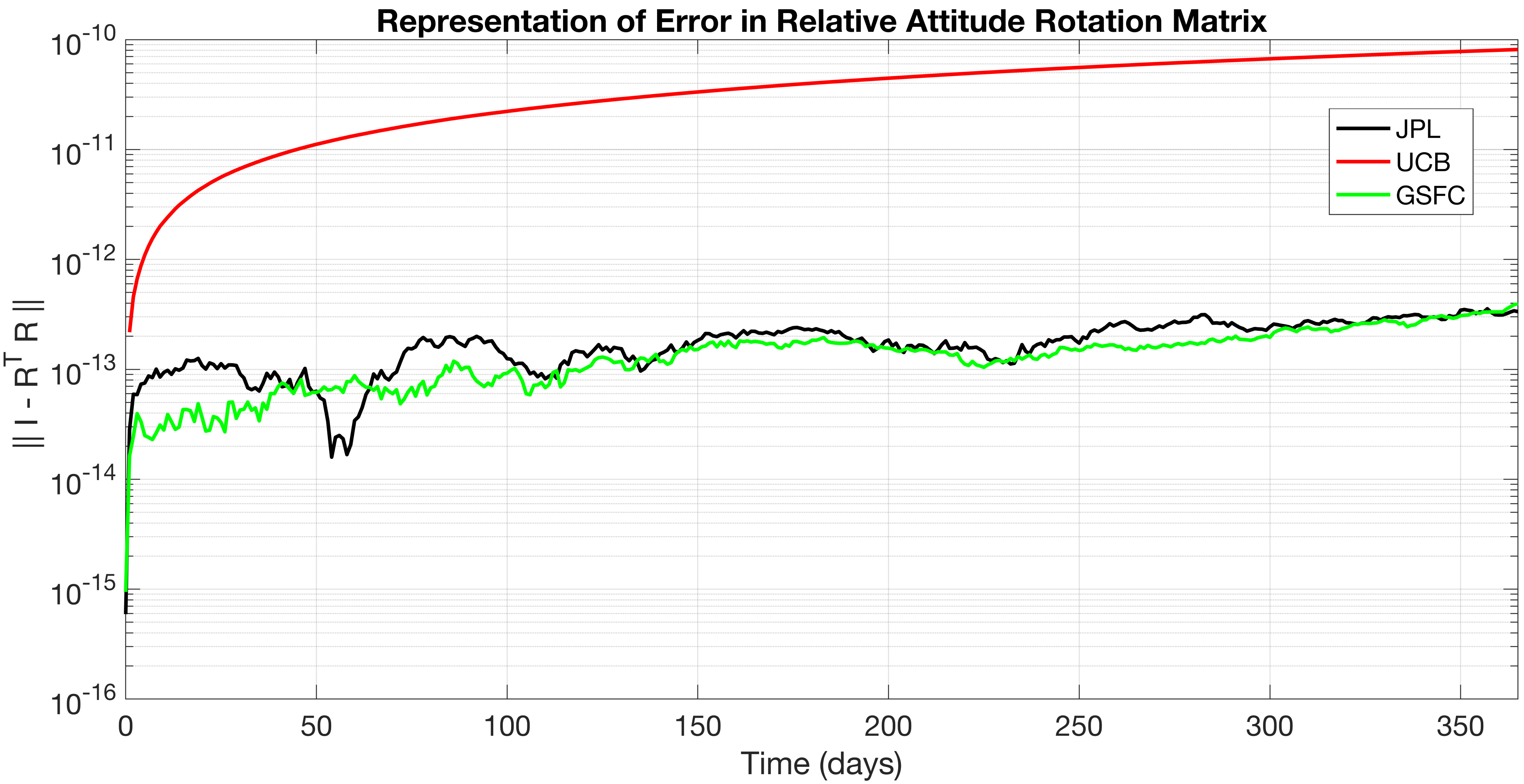
Benchmarking Results – Two Ellipsoids

Growth in Fractional Error for Conserved Quantities



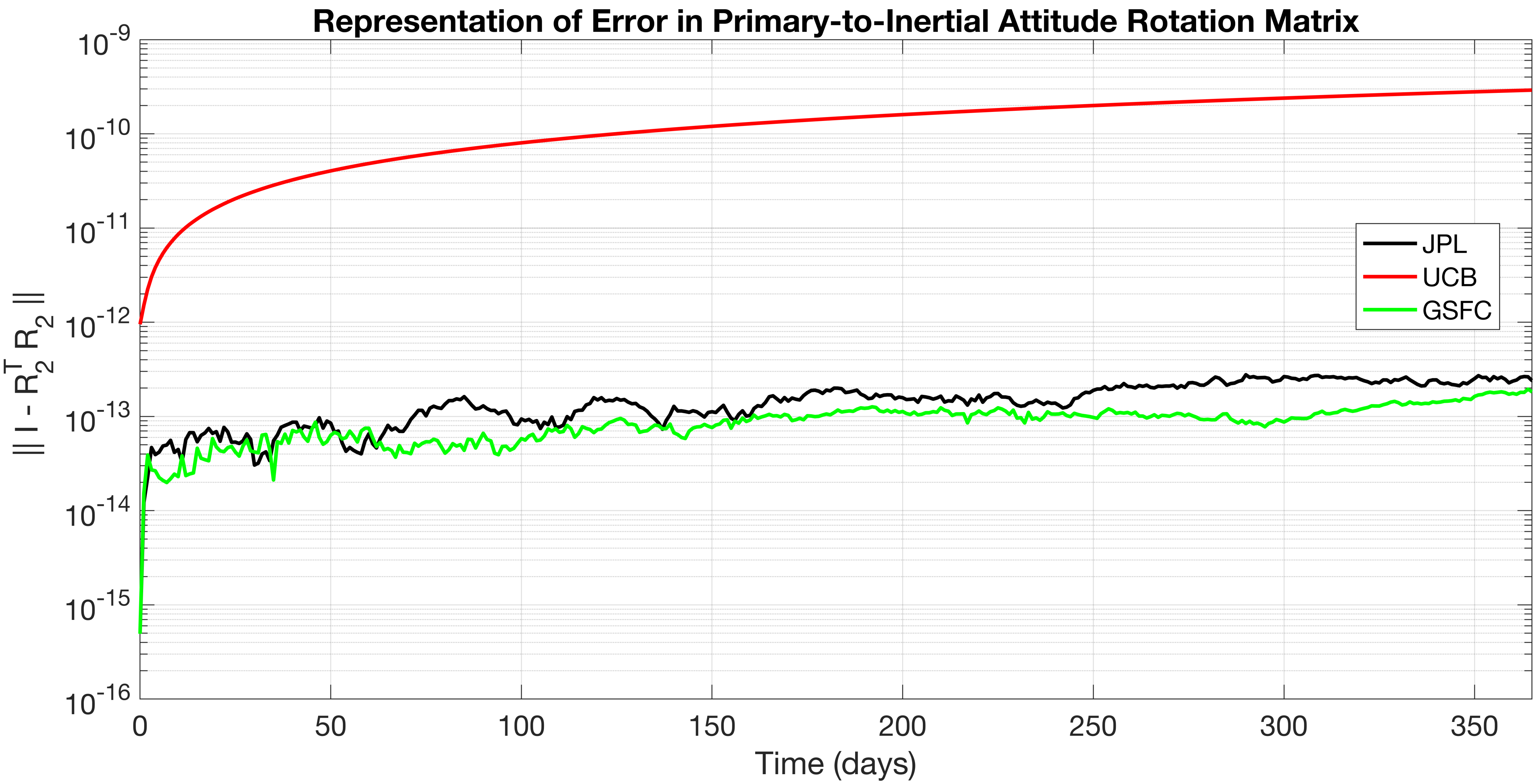
Benchmarking Results – Two Ellipsoids

Divergence of attitude from SO(3) group, the geometry of rotational dynamics



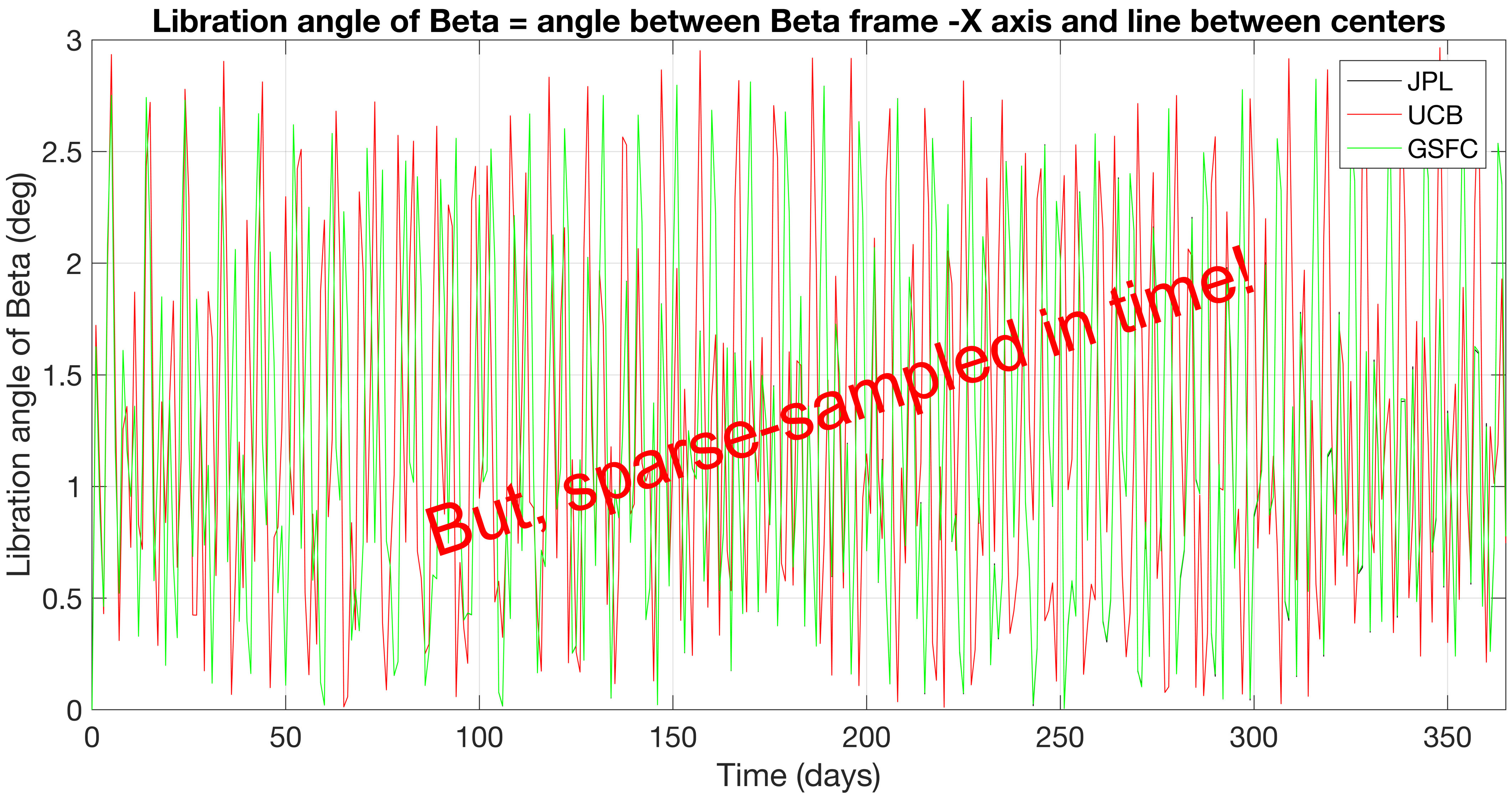
Benchmarking Results – Two Ellipsoids

Divergence of attitude from SO(3) group, the geometry of rotational dynamics



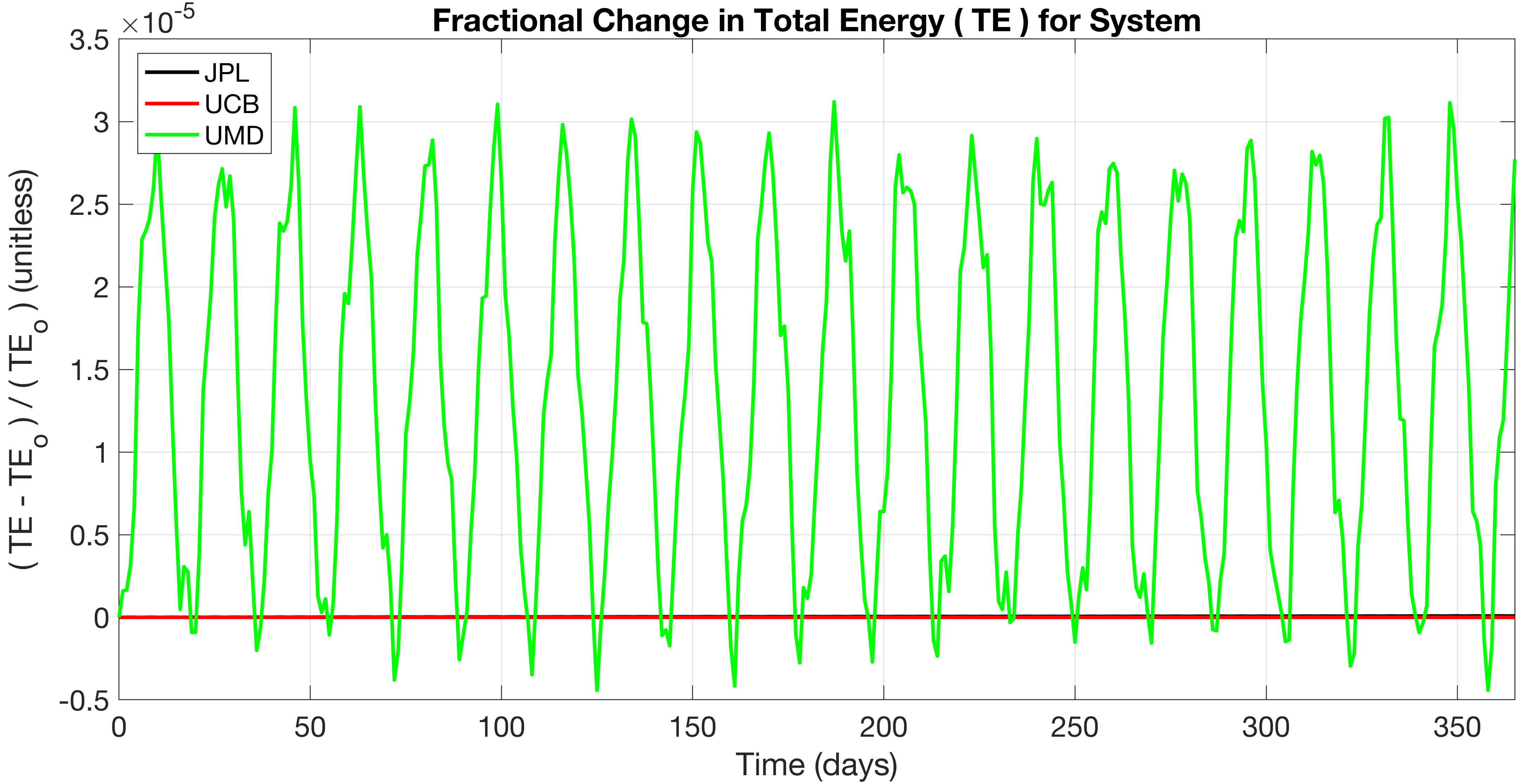
Benchmarking Results – Two Ellipsoids

Secondary's initial angular velocity deviation → bounded forced libration



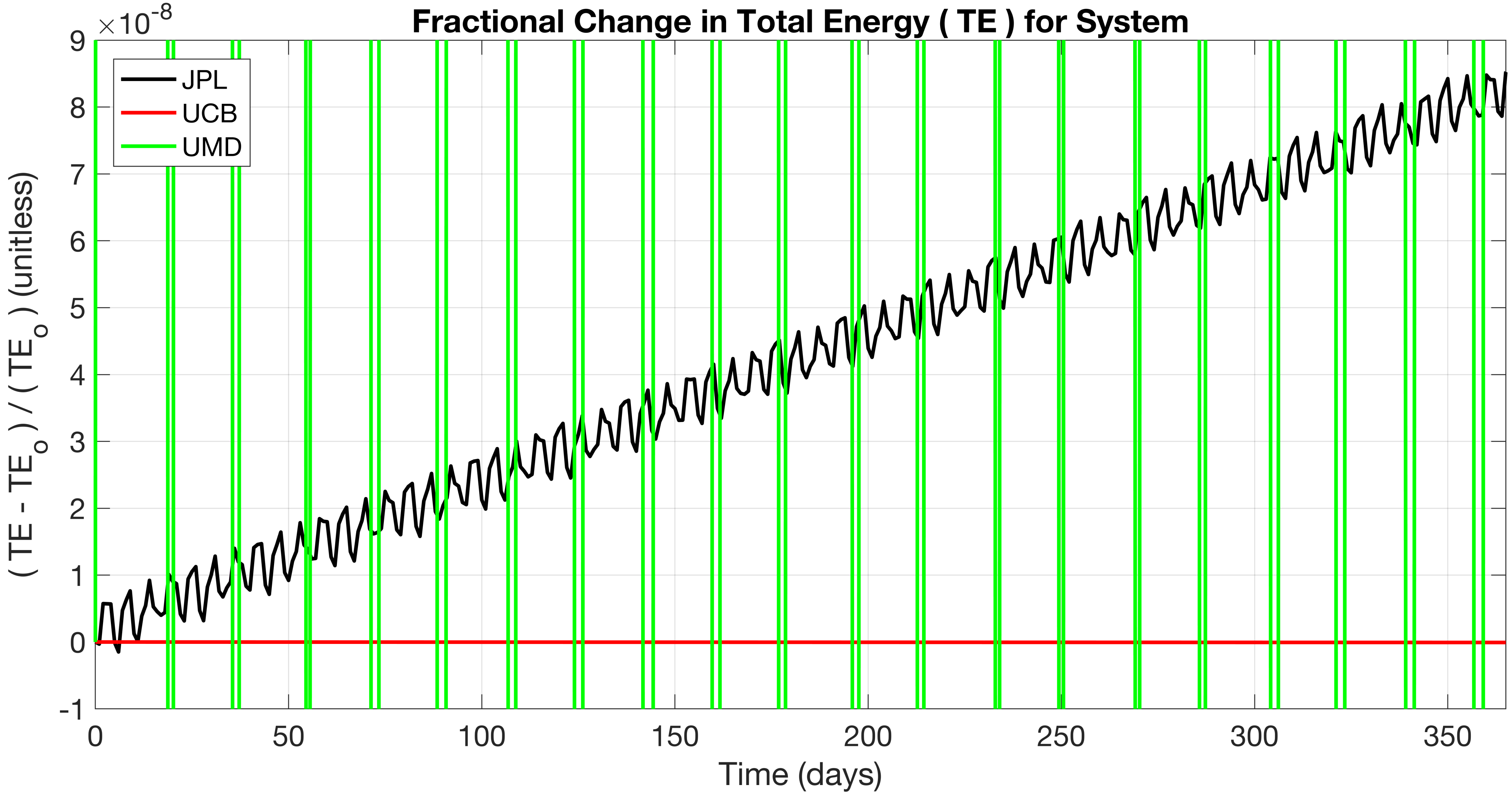
Benchmarking Results – Full Didymos

Growth in Fractional Error for Conserved Quantities



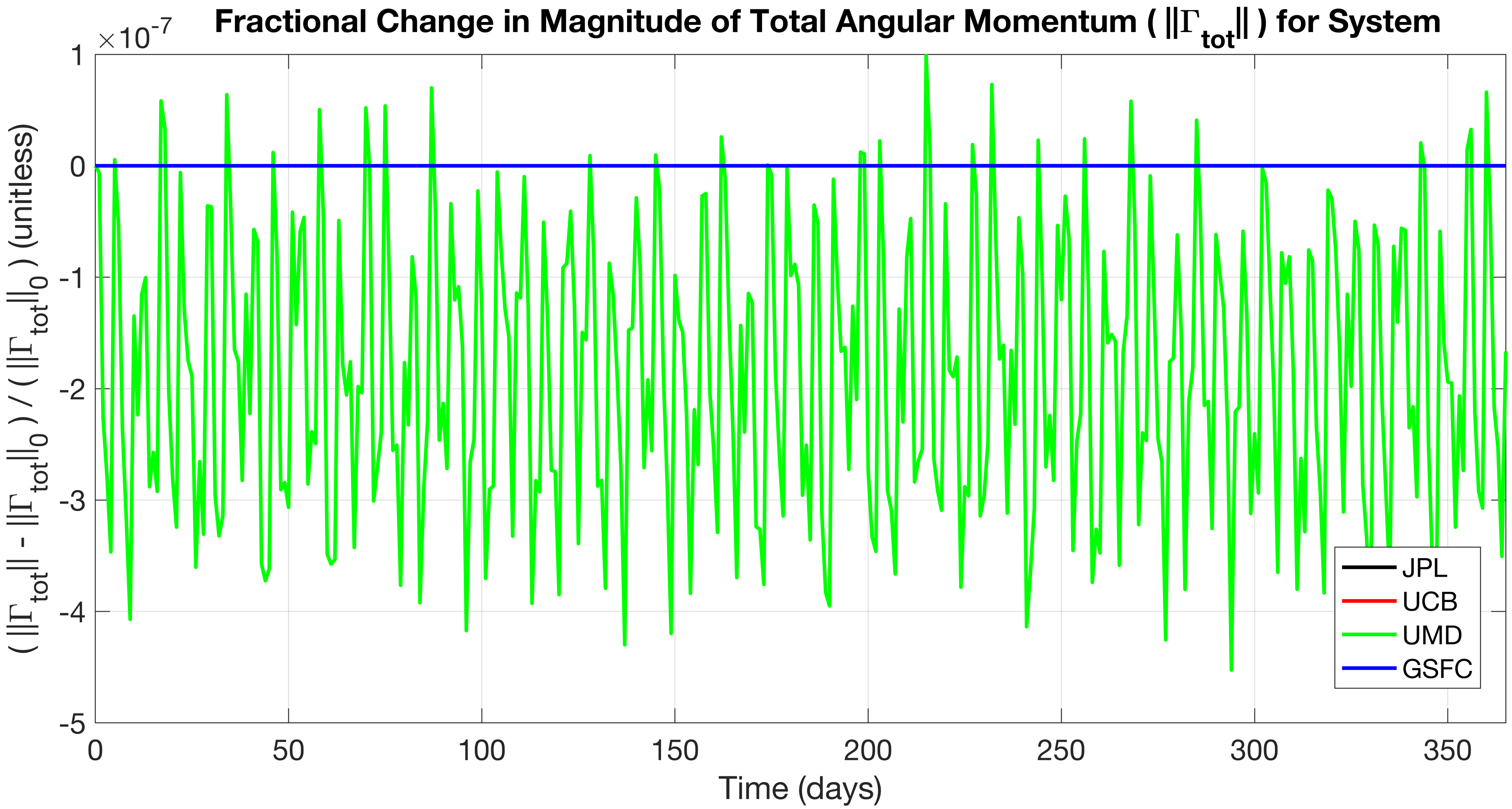
Benchmarking Results – Full Didymos

Growth in Fractional Error for Conserved Quantities



Benchmarking Results – Full Didymos

Growth in Fractional Error for Conserved Quantities



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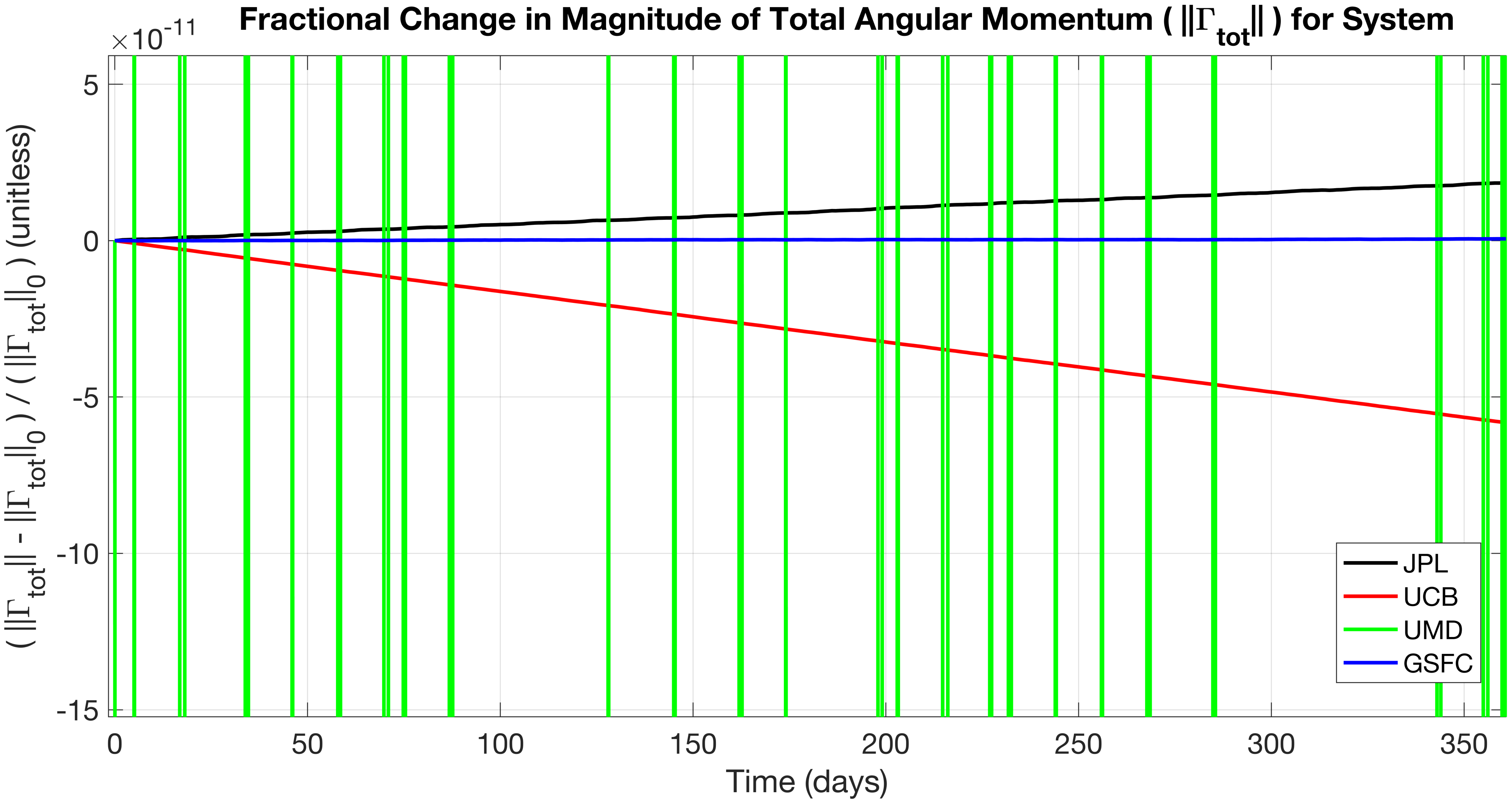
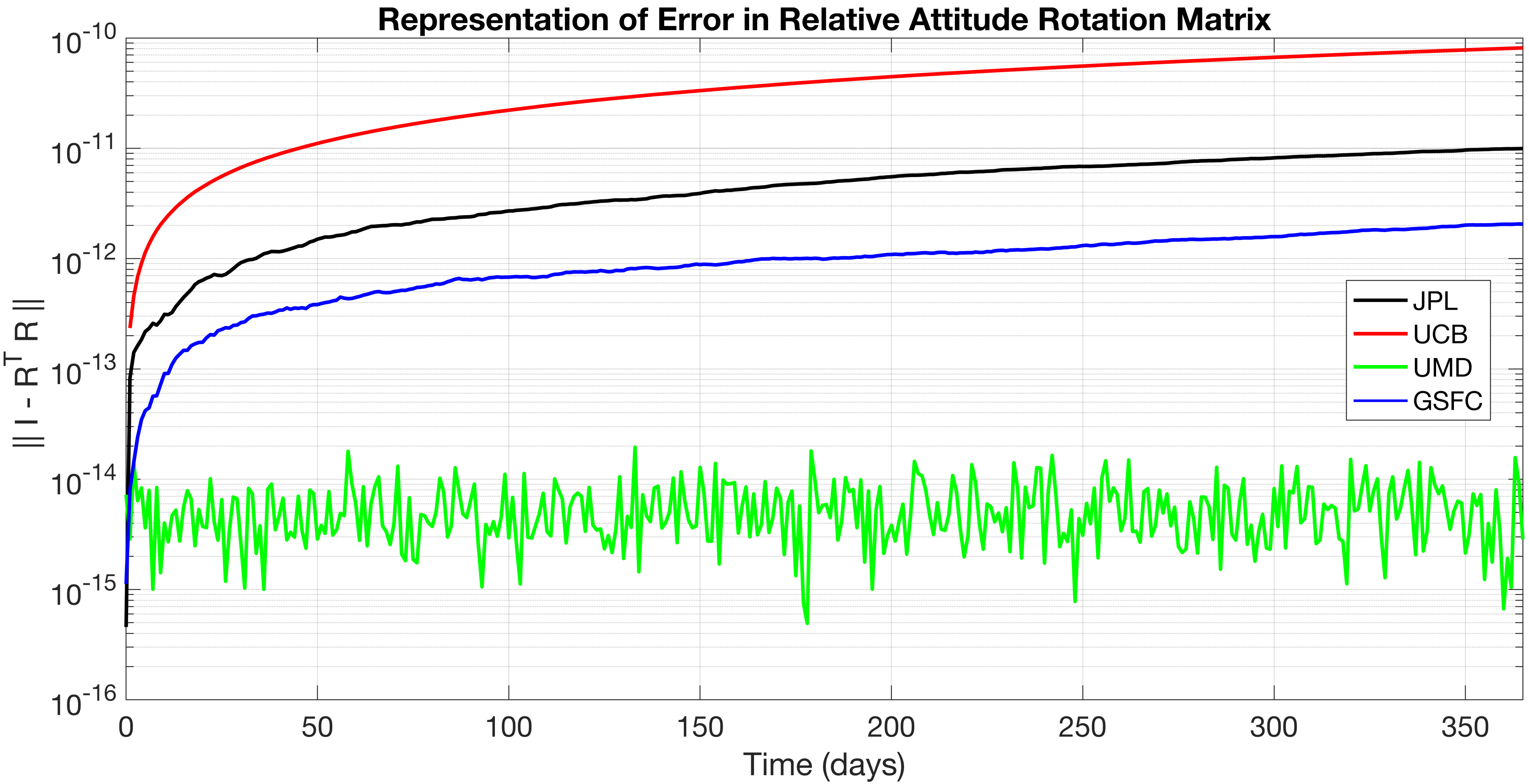


Benchmarking Results – Full Didymos

Divergence of attitude from SO(3) group, the geometry of rotational dynamics



Benchmarking Results – Full Didymos

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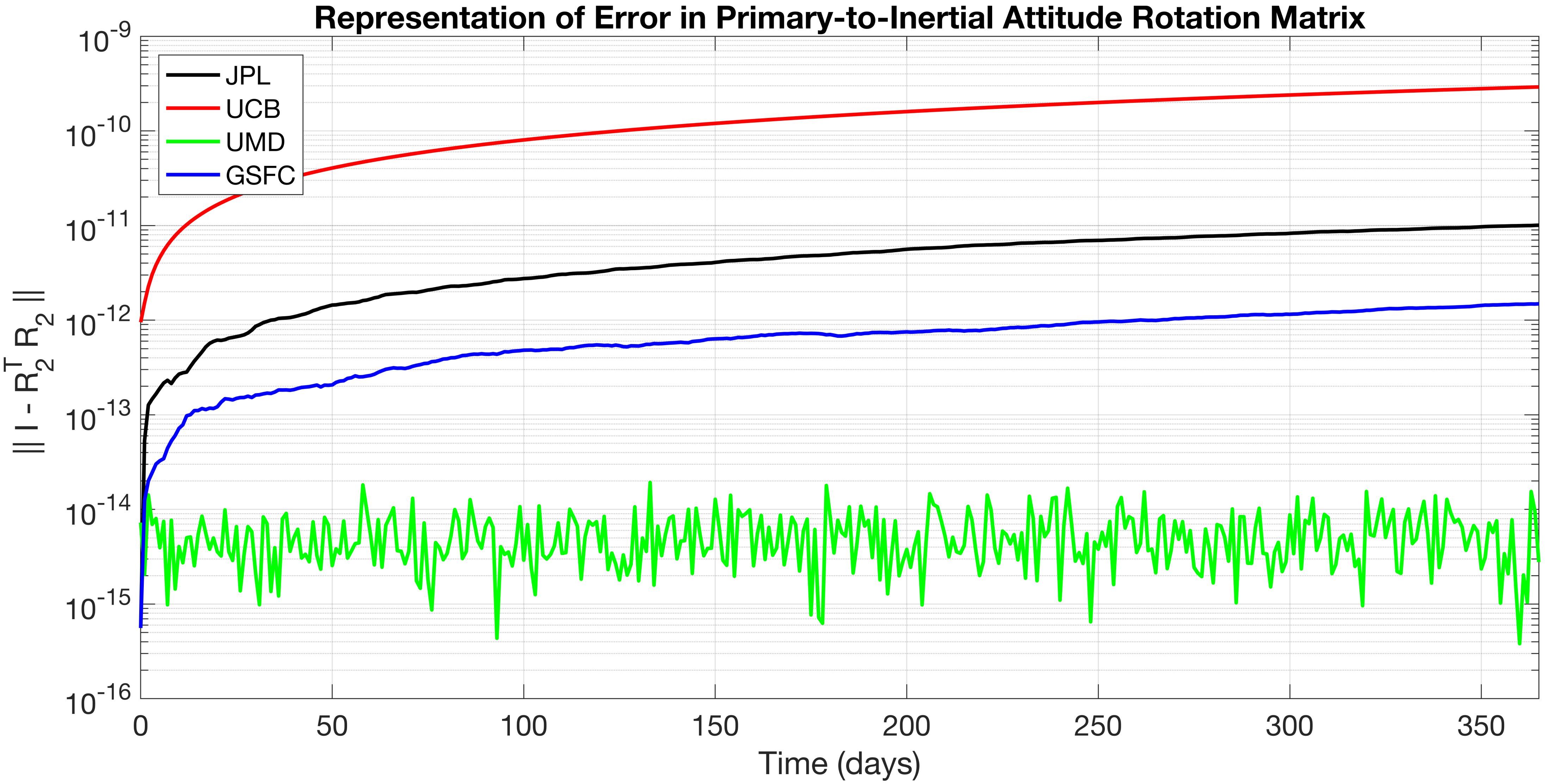


Benchmarking Results in Summary

Relative performance of participants, by metric, by model

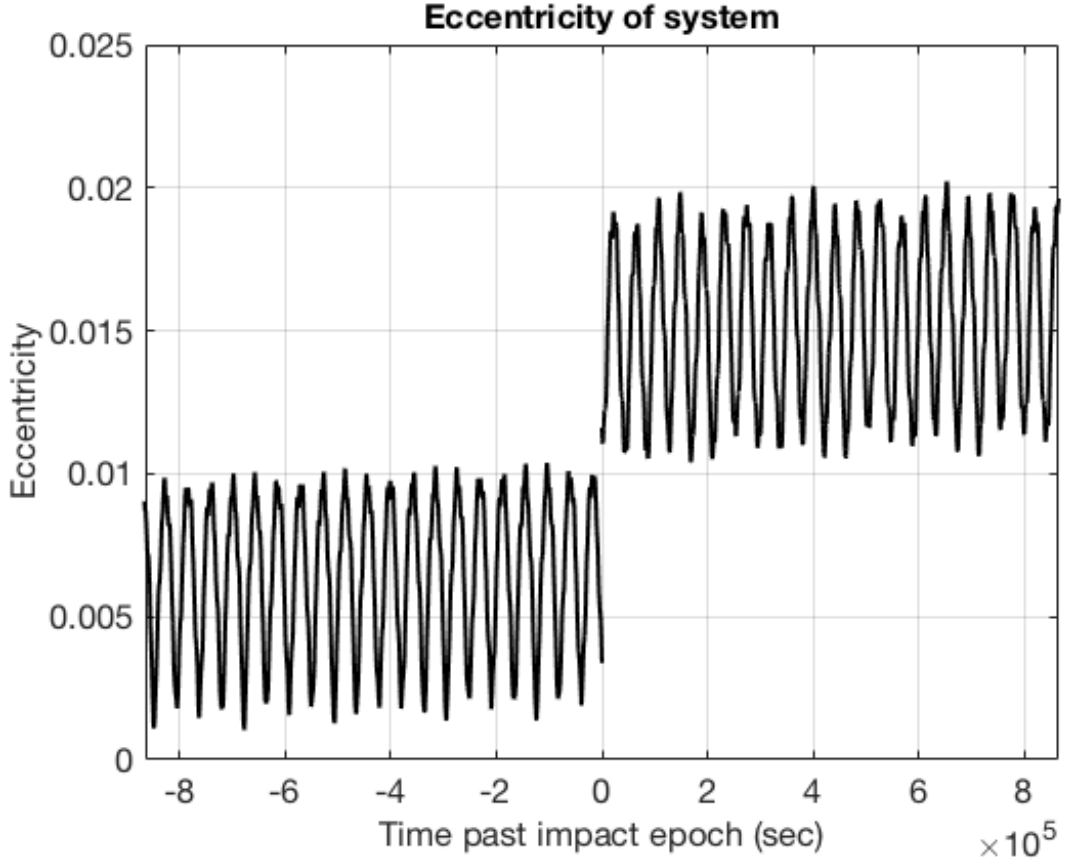
Metric	Two Cubes	Two Spheres	Two Ellip.	Didymain + Ellip.
Fractional Δ in TE	UCB > AU > JPL	JPL > UCB	UCB > JPL	UCB > JPL >> UMD
Fractional Δ in TAM magnitude	JPL > GSFC > UCB > AU	JPL > GSFC > UCB	JPL > GSFC > UCB	GSFC > JPL > UCB >> UMD
$\|\|I - R^T R\|\|$	JPL > UCB≅GSFC > AU	GSFC > JPL > UCB	JPL ≅GSFC > UCB	UMD >> GSFC > JPL > UCB
$\|\|I - {R_2}^T R_2\|\|$	JPL > GSFC > UCB > AU	GSFC > JPL > UCB	JPL ≅GSFC > UCB	UMD >> GSFC > JPL > UCB
Non-synchronous rotation or libration of secondary	JPL & UCB consistent	all are consistent	consistent in mag., not in phase	consistent in mag., not in phase

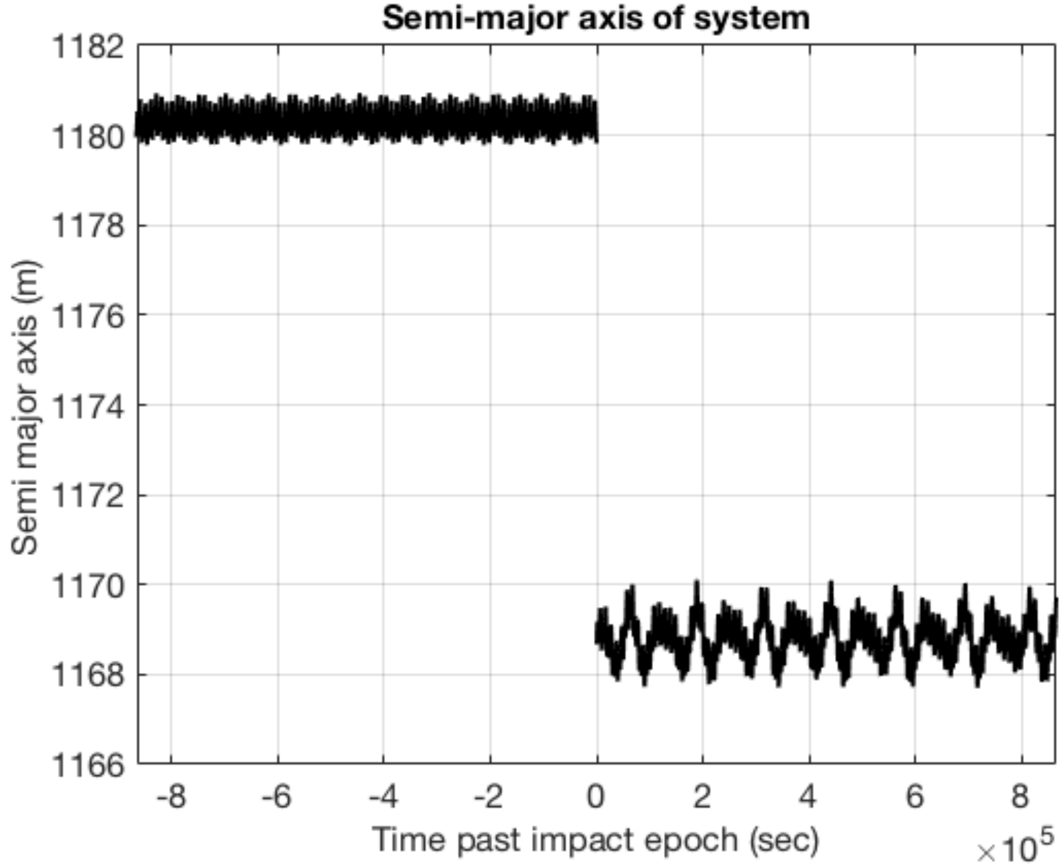
** All results are highly preliminary at this stage!
Analysis is ongoing

Modeling Changes Induced by DART Impact

Representative Example Case

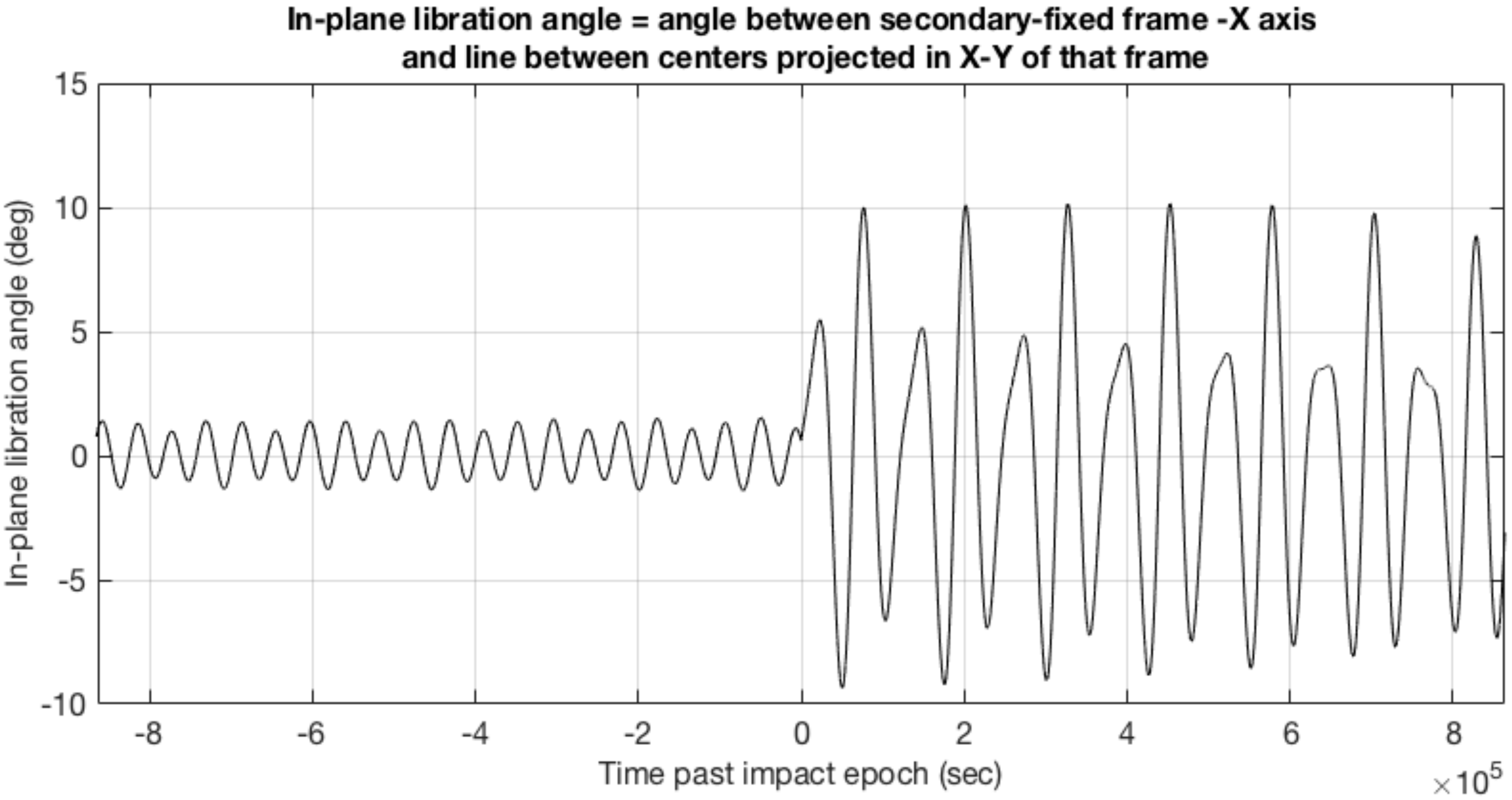
- **Initial 3° misalignment of orbit pole and primary spin pole → co-precession**
- **Initial 0% mutual orbit eccentricity, & relaxed libration**
- **Momentum impulse matching $\beta = 2$ applied a little off COM…**





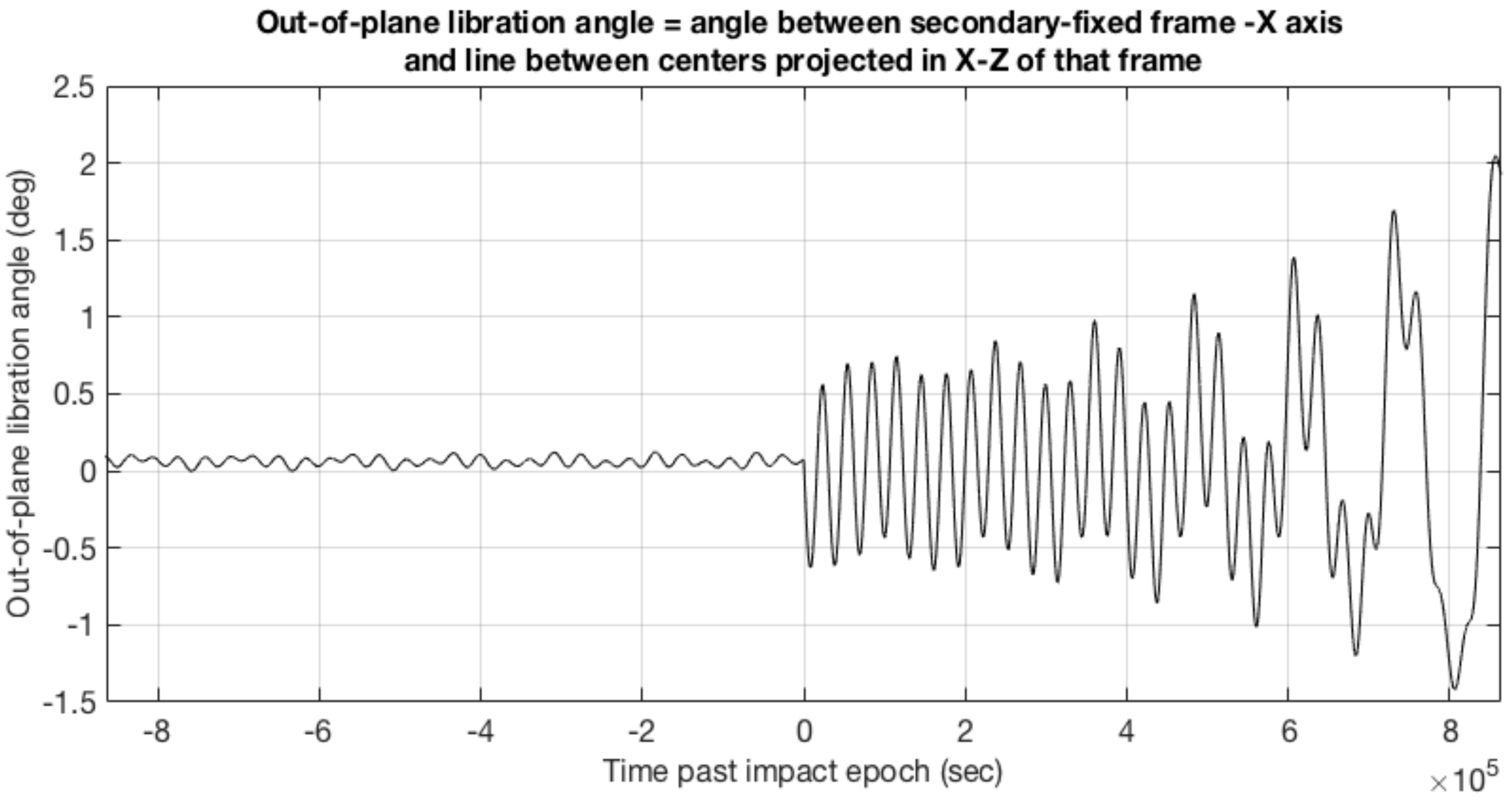
Modeling Changes Induced by DART Impact

Representative Example Case



Modeling Changes Induced by DART Impact

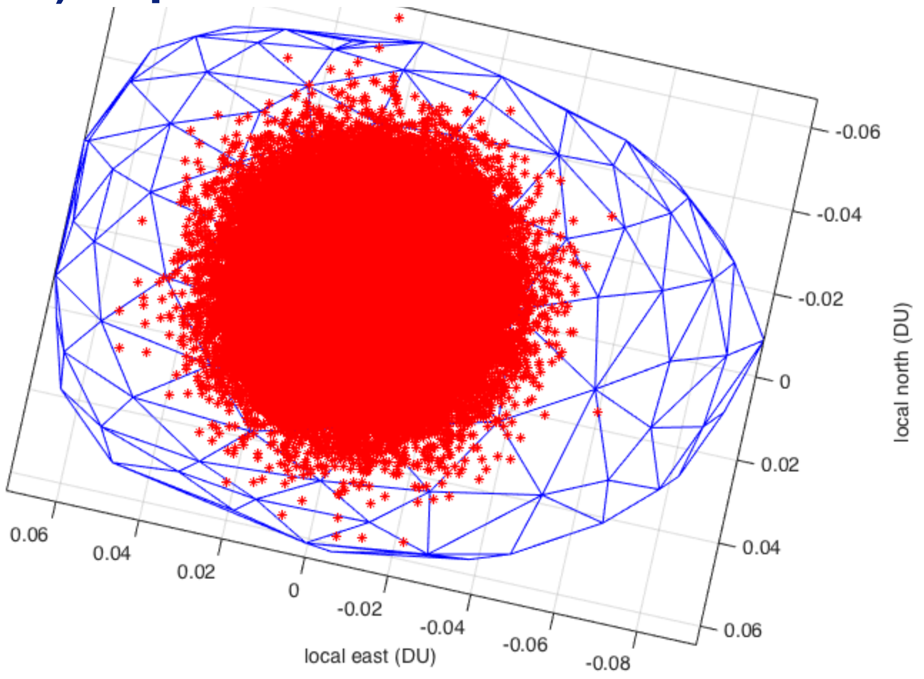
Representative Example Case



Continuing Investigations

Path Going Forward

- **DART's approach relative velocity vector is essentially fixed by now**
- **But there exists targeting dispersion about nominal (optimal) impact location = COF**
- **COF itself may be offset by several meters from COM …**
- **Currently β is highly uncertain …**
- **We are conducting sparse raster sampling of β values and impact locations and performing F2BP simulation of post-impact dynamics in each case**



Impact point dispersion on top of projection of hypothetical secondary shape into B-plane

Questions?

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.